NUCLEAR ENGINEERING VOL. 6 NO. 59 APRIL, 1961

THE AGR TODAY

BEFORE even the first of the civil Magnox stations comes into operation, the AGR at Windscale, upon which major constructional work is now complete, should be starting on its test programme. This reactor, together with its critical and sub-critical assemblies, represents a new approach to system development in the U.K., being conceived from the outset as an experiment rather than as a plant containing experimental facilities. It will be recalled that Calder was built to make plutonium, and although latterly it has been used more and more for testing elements for the civil stations, only as the need for rapidly increasing plutonium stocks has lessened have concessions been made to the experimentalists. The Dounreay fast reactor was designed as a prototype and its lack of flexibility as a result is a material hindrance to the experimental programme that it now has to meet. If the Windscale AGR had also been designed as a prototype, it is probable that the uncertainty over the canning material would have had more influence on the construction programme than has been apparent. Although not running quite to schedule, delays on completion will amount to a few months only, and these can be traced to conventional problems inherent in any novel plant project.

Background Conditions

The AGR will, however, come into operation in a very different atmosphere from that obtaining when its first outlines took shape on the drawing board. The shifts in emphasis that have affected the Magnox programme could affect the potential of the AGR system even more. But before examining this, it is useful to reconsider the lines of thought that led to its development. The gas cooled, graphite moderated reactor using metallic natural uranium was chosen as the basis for the British programme because only natural uranium was available, the price of graphite appeared more favourable than that of heavy water and safety considerations dictated gas rather than water cooling. Over the years the price of reactor grade graphite, machined to the required shapes and tolerances, has tended to go up—a figure of £500/t now seems minimal—whilst the price of heavy water has gone down, and in view of the success of the Russian graphite moderated water cooled reactors as well as the stability of the BWRs, one suspects that the safety problems associated with water cooling were given too superficial a study.

However, with the knowledge that was available it seemed not only reasonable but inevitable that we should proceed through the air cooled Windscale piles to the CO_2 cooled reactors of Calder, Berkeley, etc. to Sizewell and beyond. The civil reactors were always regarded as base-load stations which, because of their inherent high capital cost, were able to compete with conventional plant only at high-load factors. Then in order that nuclear energy should be capable of taking over an increasing proportion of the peak load, it was necessary to develop a lower capital cost system, even at the expense of an increased fuel cycle cost. Decreased capital costs indicated higher power densities and higher thermal efficiencies, both of which led to a need for a fuel enriched in U^{235}.

And so the AGR was born—the logical adaptation of the Calder system to the new requirements. Glossed over was the fact that we were reversing the conditions that led to the adoption of the Calder reactor in the first place. Once we had accepted the principle that enriched fuelling was permissible, our position differed little from that of the Americans and we could have gone back to the beginning to consider the whole range of reactors that might meet these completely new parameters. True, some sop was paid to the original principles by the proposal to use beryllium as a canning material and so limit the level of enrichment necessary, and we had by that time already built up a great deal of experience in the engineering implications of gas cooling. But it must be made clear that the AGR is, nevertheless, so far removed from the Magnox reactor that we could have begun work on a completely fresh system with very little additional penalty.

Even so, we must acknowledge that if we had indeed started to consider the next reactor system from first principles instead of as "a logical successor to Calder," we might have come to the same conclusions. What we must be wary of now is pursuing modifications to the original concept to absurdity and continuing to ignore changes in the overall power reactor climate. The system as it now stands has already evolved and the first core at Windscale is to use stainless steel canned elements of (moderately) high enrichment. There is still great concern over the irradiation induced graphite-CO_2 reaction, which, being independent of temperature but directly related to power density, is of much greater importance than the straight chemical reaction at temperatures up to 600°C, and there is even talk of the possibility of having to design power station AGRs with removable cores. A first approach might be to dispense with CO_2 as coolant and use helium, and we could at least claim that we were producing a logical progenitor of the HTGC. One can envisage, however, that side reactions on graphite would still be important, and because of our previous background we then decided to replace the graphite with beryllium. Our logical evolution then leads us to an enriched, helium cooled, beryllium moderated reactor with stainless steel cladding—a system, incidentally, already being studied by General Atomic. A similar process of development which ignored changes in fundamentals (in this case the change over from air to CO_2 cooling) is demonstrated in the evolution of magnox A 12; the French, starting, as it were from scratch, went almost directly to the magnesium zirconium alloys.

Fortunately the properties of Magnox are adequate and no serious loss of time has resulted.

Beryllium Versus Stainless Steel

But to return to the AGR; the important matters to consider now are its present status and its further potential, in the light of increased knowledge and the changed conditions in the nuclear engineering field. The chance of the original beryllium concept being adopted in large power stations becomes steadily more problematical. Of the many difficulties associated with its use, most have been successfully resolved, and its practicality as a canning material has, at least in loop work, already been demonstrated. There remain two major hurdles; the first is break-away corrosion, and the second concerns the economics. The corrosion behaviour is strongly similar to that experienced with some zirconium alloys in water environments, i.e., the break-away point and rate are critically dependent upon some property of the material that is at present outside the scope of normal material specifications. One can assume, however, that a solution will be found to this, as some samples have exhibited good corrosion resistance, but for a long time a high rejection rate of complete components must be anticipated. The second problem is the more intransigent.

The U.K.AEA have been reluctant to release figures of the costs of uranium enrichment or beryllium fabrication, but certain broad facts have emerged which allow approximate calculations to be attempted. In their request to industry to tender for Magnox stations the CEGB have quoted the additional costs that would be incurred if the designs included any enriched fuel. The curve of enrichment against price (as might be expected in view of the demonstrated theoretical justification) follows that quoted by the U.S.A. in their published figures. For example, elements containing uranium of $1{\cdot}2C_0$ would cost £14/kg more than natural uranium, $1{\cdot}5C_0$ material £25/kg extra. Assuming these figures are more generally applicable (and if not, one wants to know why) then the additional cost of U.K. enriched fuel over natural fuel is 1·65 times that of the Americans. On this basis, 1 kg of uranium containing 2·5% U^{235} (the figure quoted for the stainless steel elements in the Windscale AGR) would cost £60 more than the same weight of 1·8% fuel (the enrichment quoted for beryllium clad elements). Reports place the present costs of beryllium fabrications staggeringly high, but even if it is assumed that these will come down with experience, and rejection rates are not exorbitant, it is difficult to believe that cladding 1 kg of fuel in beryllium would cost less than £25 more than cladding the same fuel weight in stainless steel. This leaves a net gain per kg of fuel of £35 for a new charge in beryllium. If one now assumes that burn-ups of 10 000 MWd/t can be obtained with either cladding (and in both cases this has to be statistically demonstrated), and due allowance is made for the lower conversion factor in the more highly enriched core, the buy-back price of the fuel could be expected to differ by about £40/kg, and the scrap value of the beryllium could be in the region of £5/kg of fuel.

If these figures prove correct, the fuel cycle costs are equal. Any increase in the burn-up of the stainless steel clad elements or drop in the price of enrichment (and the reverse is much more improbable) and stainless steel cladding would show an economic advantage. In any case, we believe that before beryllium were adopted by the Generating Board it would have to show a very real economic advantage, not just equality, and there is no justification for the establishment of a large construction programme simply because this could bring beryllium costs down. Only if there were no other system or fuel would it be permissible.

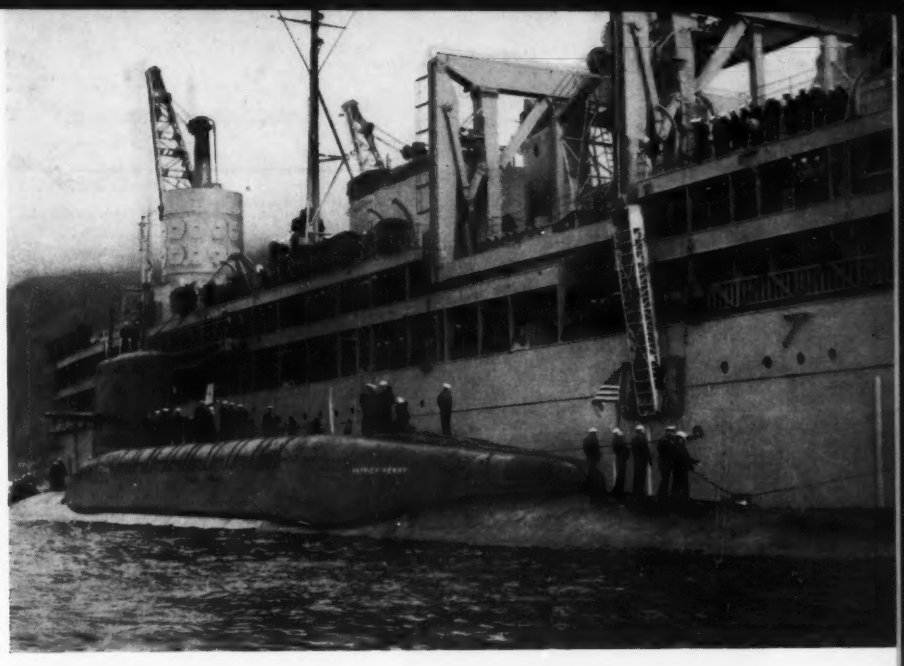
AGR Versus Magnox

We must now compare the overall economics of the AGR with the Magnox stations. On present estimates of enrichment costs and fuel burn-up, the fuel cycle costs for an AGR would seem to lie between 0·2 and 0·22d/kWh as against Magnox fuel cycle costs of 0·1d/kWh (and this last one expects to see come down). To counteract this, the contract price of an AGR (excluding site costs) will need to be some £30/kW lower than the contract price of its Magnox equivalent, if both are working at 75% load factor. We suggest that more than one AGR would need to be built before this figure could be achieved, and the Board would have to be very sure that ultimate gains would justify the initial investment.

Not that this is surprising; the AGR was conceived as a partial load station and its usefulness was to lie in conditions where load factors less than the 75% quoted would be encountered. Unfortunately it now seems clear that as we are prepared to accept a three fuel economy, for some time oil or coal will be more economic, when low load factors are being considered. So it is only over a narrow range of load factors that the AGR is likely to offer immediate economic advantages in the U.K. One must also consider that in 20 years' time, when the capital cost of the Magnox reactors is amortized, they will generate power, even under peak load conditions, cheaper than any other system possibly could.

Conclusions

We are not trying to decry the work that has been done on the AGR system nor prejudge results of the Windscale experiment before it has begun. What we do urge is that our reactor policy should change with our fuel policy and that when fundamental conditions alter, then our reactor programme be reconsidered from fundamental standpoints. The Windscale AGR is a first class experimental tool, and it would be highly prodigal not to extract from it the maximum experience possible. It would be equally foolish simply because it exists to rush ahead and prematurely decide to build a series of power reactors based on the system before real economic inducements had been demonstrated. The work on beryllium even cannot be dropped immediately, but we are fast approaching the time when this must be very seriously considered. Further, before we go on and try to adapt the AGR to an export reactor or for some other purpose, we need to be very sure that there are no systems that would better fulfil the new needs. Also if the AGR itself, or parts of its original concept, do not come up to expectations, let us cut our losses and frankly admit it. If no research projects end in culs-de-sac, then the research programme must be regarded as lacking in initiative and enterprise. In the meantime, whilst we evaluate the AGR, let us do more than conduct prejudiced studies on alternative systems. Now there is no urgency to introduce a partial load nuclear station let us use the development strength we possess, both within and outside the U.K.AEA, to gain practical knowledge of the organic and light and heavy water systems, so that future policy makers in the power and propulsion fields are provided with a solid background of experience on which they can base their own decisions. If we continue just to extrapolate the past we shall present them with a fait accompli, a restrictive line of reactor technology devised and developed in completely alien circumstances.



The U.S.S. *Patrick Henry* alongside the depot ship, *Proteus* in the Holy Loch, Scotland.

World Digest

International

Organic Design Studies

TWO contracts have been signed by Euratom for a detailed preliminary design for its 50 MW(th) reactor project, Essor—the first stage in Euratom's programme (Orgel) for the development of heavy-water moderated, organic-cooled natural uranium reactors. One contract is with Groupement Atomique Alsacienne Atlantique, in association with Interatom, and the other with Indatom, in conjunction with Belgonucléaire and Siemens. Plans have to be submitted by June. Euratom will then select one of the participants for further studies, and later for construction of the reactor at, most probably Ispra, starting in 1962. The purpose of Orgel, to which $6 million have been allocated for 1961, is to prepare the way for industrial construction of power reactors of this type. Fourteen research contracts have already been signed with European companies and institutions for work on the programme.

A radioisotopes bureau is to be established by Euratom. Its main function will be to distribute literature on isotope applications. A committee of experts will be set up to advise on this work.

A contract for co-operation on the promotion of experimental and theoretical research into controlled thermonuclear fusion has been concluded between Euratom and the Plasma Physics Institute, Garching, near Munich.

A working agreement between Euratom and Britain was urged by Mr. E. M. A. Sassens, a Euratom commissioner, at a recent meeting in the House of Commons. He said an agreement could be reached without any legal modifications to the existing co-operative arrangements being necessary.

£10 has been allowed for nuclear marine propulsion in the Ministry of Transport estimates for 1961-62. This purely nominal figure is included to ease Parliamentary procedures in the event of a definite project being put into effect.

Civil estimates for 1961-62 include a net figure of £78 325 000 for the AEA, £15 215 000 less than the vote for 1960-61. The capital programme has been reduced and there will be a cut in expenditure on raw materials, due to the stretch out of the South African uranium contract and the ending of the Congo arrangements. A build up in the Authority's receipts from fuel element sales has also added to the reduction in the Government's contribution.

Harwell Reactor School's next course for senior technical executives is from May 8-19. The first week will be held at Harwell and the second at Durley Hall, Bournemouth. The fee is 50 gns. Further details can be obtained from the school manager.

The 10 kW Nestor at Winfrith achieved criticality for the first time on March 13. A modified Jason, it will be used as a neutron source for sub-critical assemblies. Descriptions of its design and some of the experiments to be carried out with it appeared in *Nuclear Engineering*, November, 1960.

A public inquiry is to be held by the Ministry of Power into the CEGB's proposal to build a nuclear power station at Wylfa, Anglesey (*Nuclear Engineering*, January, 1961).

United Kingdom

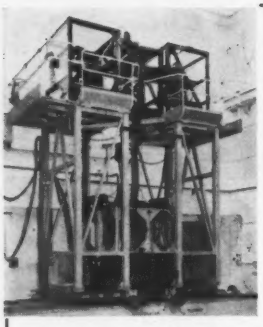
The CEGB nuclear laboratories, Berkeley, are to be officially opened on May 29. Although these will make an important addition to the Generating Board's facilities and a total staff of approximately 500 will eventually be recruited, some two-thirds of the Board's research effort will still be devoted to conventional plant development. To coincide with the opening an international conference of invited participants is being held to discuss the properties of reactor materials and the effects of radiation damage.

The Royal Assent has been given to the Electricity (Amendment) Act, the purpose of which is to enable CEGB reactors to be used for radioisotope production.

The British Standards Institution have appointed a nuclear energy industry standards committee for the purpose of directing the activities of the four technical atomic committees set up four years ago for drawing up standards in nuclear energy nomenclature, reactor technology, radiation protection and radioisotopes. It will decide upon the policies to be pursued by the committees as well as to guide them in their proposals.

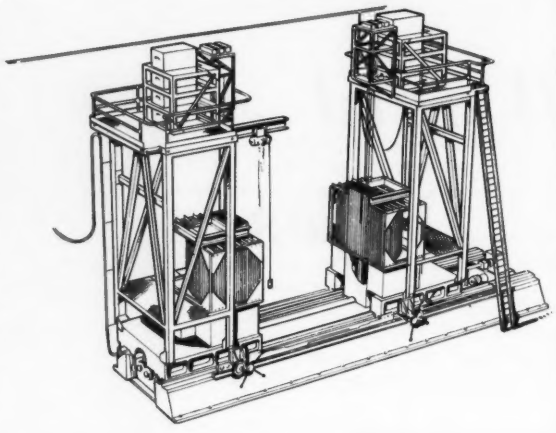
Britain's Attitude Towards Foratom

IN Britain's attitude towards Foratom it looks as though she is in danger of repeating her mistake over Euratom. At a recent Press conference in London Mr. Stanley Steward, director of BEAMA, commented that it was too early for the U.K. to join the inter-European forum. Although BEAMA was only one of the " interested " organizations represented at the March 3 FBI meeting convened to discuss this question, it is a reasonable supposition, in view of FBI's secrecy, that this comment reflects the tenor of that meeting. While the Foreign Office and Board of Trade supported a union, the nuclear industry as represented by existing trade associations felt Foratom was not the sort of organization to be of any use at this stage in " bridging the Channel." It is true that its purposes and effective spheres of influence are, at the moment, ill defined, but it cannot be ignored that it is the members who make an organization, and Britain would surely be a strong, influential partner. The matter is receiving further consideration from the FBI and it is conceivable that following a full appraisal of Foratom, industry might, even if reluctantly, change its present chauvinistic attitude. The question of whether the U.K. should set up its own Forum is also being considered, quite apart from the Foratom problem. The possibilities in such an organization are seen, but at the same time there is a feeling from existing associations that nuclear energy is already well catered for—an inevitable source of opposition. Further, there is a sneaking resentment by industry of the possible influence of what might be called the fringe interests (such as the Law Society, BMA, etc.) who are in mild support of a forum. It is influence which industry feels tends to weaken many overseas organizations, including Foratom.



Vera at AWRE

VERA (Versatile Experimental Reactor Assembly) is a 100 W facility at Aldermaston for carrying out reactor experiments to improve nuclear data and methods of calculations used for fast critical assemblies. It includes a core region of thin-walled steel fuel tubes surrounded by a natural uranium reflector — the whole forming a cylinder 4 ft high and 5 ft in dia. The fuel tubes are loaded with fissile and diluent material plates 1·7 in² and ⅛ in thick. As can be seen the reactor is designed to separate into two parts for safe loading. An accelerator associated with Vera enables neutron bursts to be used for reactivity and time-dependent behaviour measurements. The reactor is located in a large concrete cell. Initial criticality was achieved on February 22.



Afghanistan

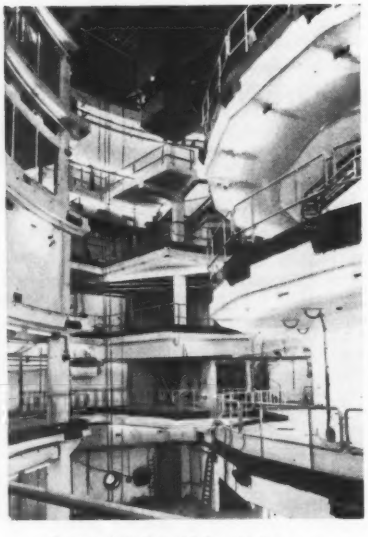
A bilateral agreement with India is sought by the president of the AEC. He proposes that in return for training Afghan personnel and supplying radioisotopes India be offered access to Afghan uranium deposits.

Australia

Current taxation concessions on the mining and treatment of uranium ore have been extended to 1968. Senator Spooner, Minister for National Development, says that the government had taken this decision after reviewing the problems likely to arise from a recession in the uranium market.

Belgium

Nearing completion at Mol is the fuel processing plant under construction for Metallurgie et Mecanique Nucleaires. It is designed for the fabrication of natural and enriched uranium fuel elements.

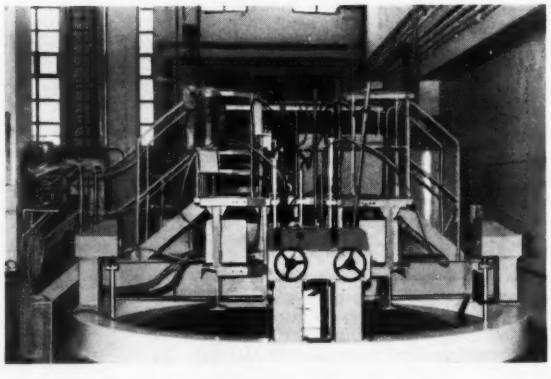


Reactor hall of the BR-2, at Mol, due to achieve criticality on April 17

Canada

The Canadian Nuclear Association is to hold a conference in Toronto, May 16-17. Its theme will be nuclear energy developments in Canada, with particular reference to the heavy-water reactor type and the future prospects for nuclear plant in the country. The conference will also be CNA's first annual meeting and the opportunity will be taken of explaining and developing the aims of the Association and relating them to the work of similar overseas organizations.

France



Top of Peggy, the critical assembly designed for providing data for Pegase, the light water tank reactor to be built at Cadarache. Moderating and cooling water is contained in a 6 m high, 4 m dia. vessel and there are 25 fuel elements of 20% enriched uranium. Criticality was achieved on February 2.

Construction work has started on Pegase at Cadarache. A 30 MW(th) light water tank reactor, it is to be equipped with eight test loops which will be used for investigations on prototype EDF 2 and 3 fuel elements. Pegase is expected to be ready for use in late 1962.

Bureau Veritas, the international register for classification of shipping and aircraft, Paris, have issued a guide to general technical conditions for nuclear shipping. The guide, which is available in English, covers measures to be taken in preventing accidents, in evaluating accidents and in reactor operation.

West Germany

Construction of Dido at Jülich is expected to be completed during May. High power operation is expected by the autumn.

An office for nuclear economics has been created by the Schleswig-Holstein ministry for economics and traffic. Its purpose is to aid local industry in preparing itself for developments in the nuclear field.

Because of porous welding the aluminium reactor tank for the FR2 at Karlsruhe will have to be renewed. Constructors of the tank, W. C. Heraeus, report that the welding process used was specially requested although freedom from porosity could not be guaranteed. No trouble was encountered with the Jülich Dido tank which they Argon-arc welded.

FR2 went critical for the first time on March 7 and is operating at 1 kW.

The contract for Atomics International participation in the KBWP 150 MW OMR design project (*Nuclear Engineering*, February, 1961) has been signed.

Official approval has been given to the construction of the 50 MW(e) heavy water multi-purpose reactor (MZFR) designed by Siemens-Schuckertwerke. Karlsruhe has been named as the site and the construction period is expected to be about three years.

Full power operation of Kahl was expected to start, at the earliest, at the end of March, according to reports from Germany. Because of the Dresden breakdown, official permission to operate is consequent upon a change in the control rods.

India

A co-operative technical agreement has been signed between the AEC and Atomic Power Development Associates, of the U.S., who are responsible for research and development on the Enrico Fermi project. APDA have similar agreements with the U.K.AEA and BelgoNucléaire.

Deadline for the Tarapur tenders has been moved from May 31 to August 31.

Italy

A site for the 30 MW(th) OMR project which has been undertaken by CNEN in conjunction with AGIP Nucleare and SORIN (*Nuclear Engineering*, December, 1960, p. 556) has been selected at Bologna and about £400 000 allocated towards its completion.

An architect engineer is shortly to be selected to work with Allis Chalmers in the construction of CNEN's thorium-uranium-233 reprocessing and refabrication pilot plant. As yet a site has not been decided upon although it is certain to be in the southern part of the country.

This year's summer course on nuclear physics at the Enrico Fermi International School of Physics is to be held from August 7-26 under the direction of Professor V. F. Weisskopf, professor of physics at MIT. Cambridge, Massachusetts, and recently appointed director-general of CERN. Applications for the course have to be submitted by not later than July 13.

Japan

The Atomic Industrial Forums of Japan and America are to sponsor a conference on nuclear energy in Tokyo, December 5-8. Information on the current status of power reactors, including propulsion units, will be exchanged and the possibility of further U.S.-Japanese co-operation on government and non-government levels discussed. It is hoped that among the speakers will be representatives of the European forums.

Monaco

The Oceanographic Institute, Monaco, the Monaco government and IAEA have signed an agreement for carrying out research on the effects of radioactivity in the sea. The work will be undertaken at the Monaco Scientific Centre; the Institute will provide oceanographic vessels and specialized fishing equipment; and the Agency personnel and technical apparatus and supplies. An annual contribution of NF200 000 will be made towards the project by Monaco.

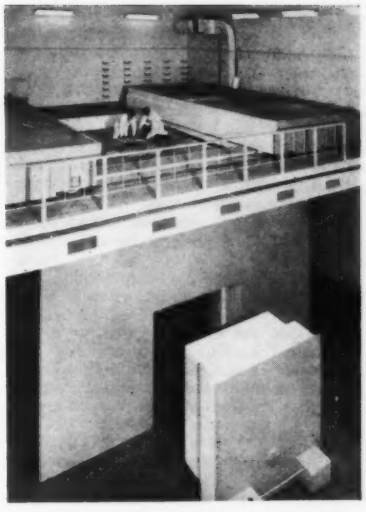
Netherlands

The success of the recently held reactor course at Petten has led the RCN to plan for such a course to be held at least twice a year. This was the second one to be organized and like the first in November, 1960, was overbooked.

The Netherlands Atom Forum has been formed. Initiated by Reactor Centrum Nederland and industry, its primary object will be to publicize, by means of publications, conferences, and information meetings, nuclear developments, and co-ordinate participation in nuclear exhibitions. The Forum will also undertake the documentation of information on nuclear energy developments and application and will represent the Netherlands in Foratom.

Norway

Delivery of the second fuel charge for the Halden BHWR is under way. Supplied by the Atomic Energy Company of Sweden (*Nuclear Engineering*, January, 1960), the charge consists of approximately 1 500 kg of 1·5% enriched uranium oxide made up into 100 7-element fuel rods assemblies of Zircaloy-clad rods. With the new charge it is expected to raise the maximum power level of the reactor from 5 MW to 20 MW. Before leaving Sweden the elements are being assembled in the RO at Studsvik—the first time this reactor has been used for comprehensive measurements on enriched fuel systems.



Nora, the heavy water zero energy reactor at Kjeller, expected to go critical around May. It will be run by an IAEA team headed by Dr. Raja Ramania of Trombay.

Philippines

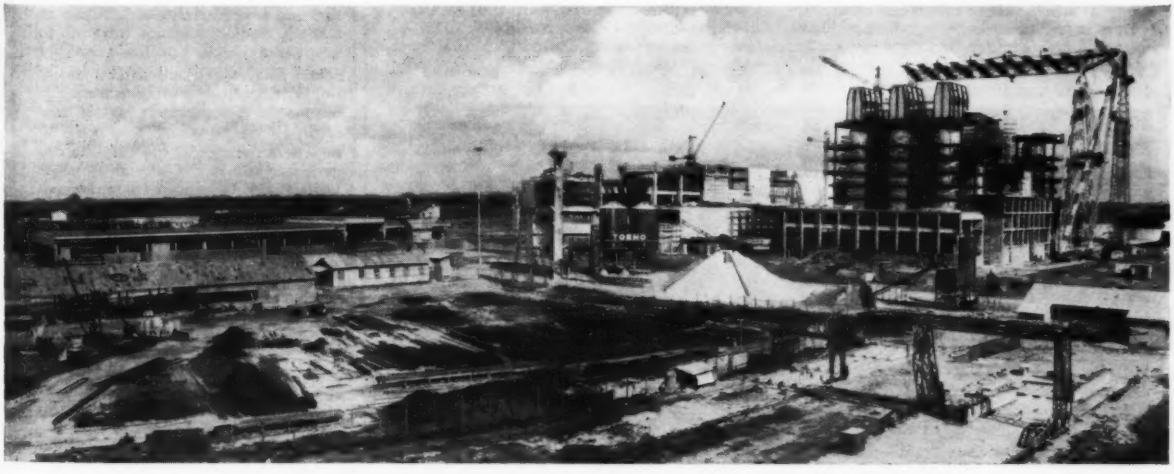
A proposed foreign investment law recently introduced into the House of Representatives allows investment by foreign nationals in a number of economic activities, but denies them the right to enterprises in certain spheres, including nuclear energy.

San Salvador

A nuclear energy commission has been established under the name of Comision Salvadorena de Energia Nuclear (COSEN).

Spain

Centrales Nucleares del Norte (NUCLENOR) are seeking official authorization for the construction of the proposed 250 MW nuclear power station at Valle de Tobalina in the north. The plant, to be known as the Bilbao-Ebro, will cost an estimated £17 million, half of which represents foreign exchange costs.



A general view of Latina. To the left is the administration block; centre, the turbine hall; right, the reactor.

Sweden

Preparations are in hand for the immediate installation of the new R2 pressure vessel when it shortly arrives from APV, of Crawley, England. The reactor will then be made critical and it is hoped to achieve the full design operating output of 30 MW(t) by the autumn. The reactor originally went critical in May, 1960, but because of faults in the pressure vessel could not be operated over 1 kW. This was sufficient to enable the reactor's low power programme to be completed.

Taiwan

Fuel for the GE pool reactor at the National Tsing-Hua University has been delivered. It comprises 23 818 g of 20% enriched uranium made up into 35 elements.

U.S.S.R.

Only one of the two reactors planned for the Kurchatov station at Beloyarsk in the Urals is now to be installed, according to reports from the States. Whether this means the Russians are confident of obtaining the station's proposed output of 200 MW(e) from one instead of two reactors, or that the graphite-moderated, steam-water-cooled superheat system is proving troublesome is not known. Original planned output of the station was 400 MW.

Viet-Nam

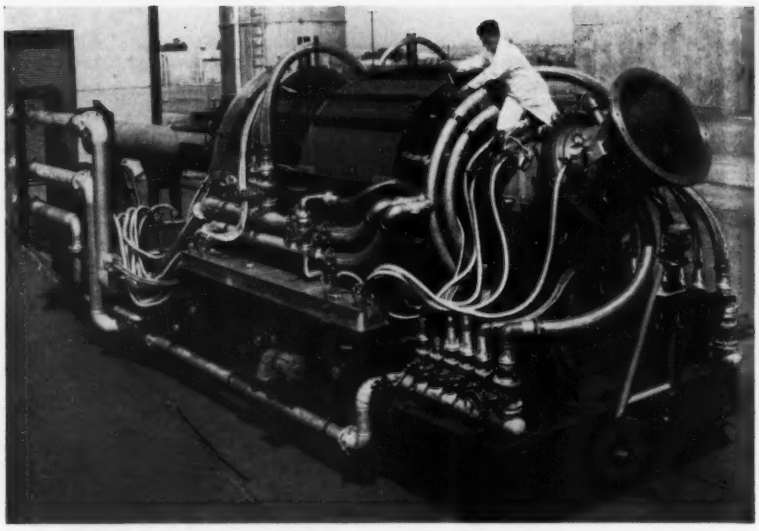
An exchange agreement has been signed with France. It provides for the exchange of information and personnel, and the supply of materials and equipment.

U.S.A.

AIF has set up a committee representing industry, labour and the universities to review the technical and procedural aspects of the SL-1 accident.

The beryllium oxide moderated nuclear assembly at General Dynamics John Jay Hopkins Laboratory achieved criticality on March 3.

Pre-start-up testing of the ML-1 at Idaho Falls has commenced. A 330 kW(e) gas cooled reactor, it will eventually be skid mounted and capable of being transported by truck, aircraft, train or barge. As reported in *Nuclear Engineering*, January, 1961, changes in the core design have already led to an even smaller core than originally planned.



Tory II-A-1, first reactor to go critical in stage I of Project Pluto, the joint AEC-Air Force programme to demonstrate the feasibility of a nuclear ramjet propulsion system. It is air cooled and the fuel consists of highly enriched uranium and beryllium oxide made up into 100,000 beryllia elements. These form a 45 in long, 35 in dia. core which is surrounded by a 2 ft thick reflector of graphite. Control is effected by eight boron loaded rotating vanes and four sliding rods. Air from the core is ejected into the atmosphere through a 38° nozzle. The whole unit is mounted on a remotely controlled rail truck to facilitate movement to the the test bed in the Nevada desert.

The AEC-NASA nuclear propulsion office have invited proposals from industry for research and development of a nuclear rocket engine. From the proposals received a contract covering the first phase of the engine development programme will be awarded. This phase will include assistance to the Los Alamos Laboratory on the Kiwi-B programme, undertaking a preliminary design of the flight engine, formulation of an engine development programme and performance of certain research and development work on non-nuclear components.

Nine utility companies have expressed interest in participating in the 50 MW OMR AEC power project (*Nuclear Engineering*, February, 1961). Following evaluation of the information supplied by these companies the AEC will invite more definite proposals.

The Martin Company are to convert part of the former Curtiss-Wright Quehenna Research Facility, Pennsylvania, into a processing facility for the production of Sr^{90} and Cm^{242} Snap fuel capsules.

No one opposed the operation of the "Savannah's" reactor at the recent public hearing held to make known the safety aspects of the ship.

Following the AEC's decision to close down the homogeneous reactor experiment (HRE) at the end of May, Dr. Alvin Weinberg, Oak Ridge director, has appealed for its continuance. He maintains that experience gained with the reactor since last year's breakdown and subsequent modification (*Nuclear Engineering*, December, 1960) indicates that a small aqueous homogeneous breeder could be designed within about two years. Estimating that the present project could be carried on for another year at a cost of about $2 million, Dr. Weinberg also drew attention to the "most painful" reduction in staff that was necessary. Over 100 at ORNL had already received notice and an additional 85-110 would have to be discharged before the year's end, he said. The AEC's reason for ending the HRE project is to concentrate on the molten homogeneous reactor concept. Dr. Weinberg has told the AEC he would not like to comment on this as it was still in the laboratory stage. When the MSR plans were announced last year, however, he showed himself a keen supporter of the system (*Nuclear Engineering*, December, 1960).

Capital cost of the Yankee reactor plant is reported to be nearly $20 million less than the estimated $57 million. The provisional total of $38·1 million is made up of $0·2 million for land, $8·7 million for buildings, $16·8 million for reactor plant, $8·9 million for generating plant and $3·5 million for ancillary equipment. During its recent 500 h long test run at full power the reactor is reported to have responded well to control.

A salt mine in Kansas where ORNL is experimenting with heated non-radioactive materials to determine the feasibility of disposing radioactive wastes in natural salt formations.

Site Problems Deter Companies

WITHDRAWAL of Los Angeles and Pasadena cities from the proposed 50 MW improved cycle BWR plant in Haskell Canyon, California, will probably lead the AEC to invite fresh proposals. Alternatively, the reactor might be built on a government site. The cities withdrew on account of doubts expressed by the Advisory Committee on Reactor Safeguards as to the suitability of the site for future expansion. As far back as last June they pointed out that there were hydrological and meteorological unknowns about the site, notably the atmospheric inversion phenomenon. Even if these factors were clarified they felt it would be imprudent to build more than one reactor here. The cities have also been deterred by the possibility of fuel, maintenance and operating charges being larger than originally anticipated. The reactor was to have been a prototype for a 300 MW plant and last November AEC announced that it would be supplied by Allis-Chalmers. Earlier in the year it had been reported that General Electric would obtain the contract. This decision was withdrawn, however, following a reappraisal of the tenders.

Delay is expected on the HTGCR project at Peach Bottom. The AEC have informed the participating companies that their research and development programme has not progressed enough to permit the issue of a construction licence. Evaluation of the safety aspects of the design is not proving clear cut. Construction of the reactor was to have started in April.

Critical and exponential work on the spectral shift control reactor concept is to be carried out by Babcock and Wilcox at their Lynchburg laboratories, Virginia. The company have been working on the basic physics of this system since last summer and the AEC have now given them permission to go a stage further. The SSCR concept involves the use of varying mixtures of ordinary and heavy water as coolant, moderator and partial control agent.

The fate of the 50 MW(e) Florida GCR project is in the balance. It is not certain whether the AEC will continue to support the research and development programme. A decision to construct the reactor was to have been made at the end of 1960. Because of a change in plans, however, it is considered that this will not now be possible until the end of 1962. It was originally intended that the reactor would use stainless steel fuel cladding and would serve as a prototype for a 300 MW unit using beryllium cladding. In May, 1960, the AEC suggested that it would be better if the problems of beryllium cladding were tackled at once and the stainless steel phase skipped. The suggestion was accepted by the companies concerned, but it meant that the Florida West Coast Nuclear Group, ultimate owners of the reactor, could not meet with the AEC's request for a construction decision by the end of the year. Although the East Central Nuclear Group, who are responsible for R and D, in conjunction with the AEC, and General Nuclear Engineering, responsible for its design, are interested in continuing the project, it is by no means certain that the AEC is.

Resumption of operation of Dresden is expected early May. A public hearing was to have been held on March 28.

After 18 months of seeking utility company interest in plans for the construction of a 16·5 MW(e) small size PWR, the AEC have decided to abandon the project. An invitation to participate was issued in August, 1959. Forty-five companies or groups responded. Negotiations were continued with two of them—Dairyland Power Cooperative, Wisconsin, and Jamestown City, New York. The sites first proposed by these organizations, however, were found unacceptable for safety reasons and new siting proposals were called for. These, however, though satisfactory from a safety angle, were uneconomic.

Major construction work has started on the 50 MW BWR plant at the Humboldt Bay Power Station, California. Scheduled for completion by summer, 1962, it makes use of the pressure suppression system of containment (*Nuclear Engineering*, January, 1961, p.61). This involves the construction of a 60 ft dia. concrete caisson sunk 85 ft below ground. The reactor contained in a 4½ in steel 10 ft dia. pressure vessel will occupy a 27 ft dia. central chamber lined with ⅜ in thick steel plate. This chamber will be attached to the outer wall of the caisson by three concrete full length supports. The resulting chambers will be partly filled with water and connected to the centre by 48 vent pipes.

Construction of the 3 MW(th) helium cooled, graphite moderated Turret reactor planned for Los Alamos has been cancelled. The AEC in its annual report for 1960 announce that it now seems " premature " and " basic information required on fuel behaviour and handling of highly contaminated helium at high temperatures can and will be developed in gas cooled loops in other reactors." About 10% of the estimated $4.9 million cost of the project has been spent.

Two irradiation sources will be installed in the $1.8 million food irradiation facility to be built at Natick, Mass., for the Army Quartermaster Corps. They will be a 1 million curie cobalt-60 source and a 24 MeV linear accelerator.

Correspondence

Atomic Jargon

Sir,—Clearly a new scientific development will need new scientific terms—atomic science no less than another. But the amount of unnecessary jargon which has been introduced appals me. I can only define it as a semantic distemper which has inflicted our technical literature.

It would not be difficult to compile a list of terms in this category but I will discuss only two here.

Biological shield. Why biological? There is nothing biological about 7 ft of concrete and it also gives protection to other than biological matter. Why not simply radiation shield?

Mortuary holes. I suspect someone thought this vaguely funny in a macabre sort of way. In fact it is a complete misnomer as the " bodies " put into them are very much alive. Spent fuel chambers would have been more apt as well as a more dignified term.

I would have said something about " facilities," with which technical literature in particular is nowadays plastered, but the opening sentence of the article on Winfrith in your November issue vindicates them all—the facilities have taken shape!

A. W. C. HIRST,
English Electric Co., Ltd.

The Economics of Separation

Sir,—A thorough discussion of the economics, design and criticality consideration in a chemical separation plant would be required adequately to answer Mr. Quartano (March, p. 99). However, an economic separation plant is continuous in operation, the dissolving rates for uranium are sufficiently low that many fuel elements must be in the dissolver simultaneously, and criticality considerations do not have a major effect on designed plant hold-up in the early stages of the purification cycle. At later stages criticality control by geometry is economically preferable to control by batch size in any plant of significant output. In consequence variations in isotopic content between individual fuel elements are not detectable in output compositions. Nevertheless, some segregation of fuel according to the extent to which it has been irradiated may be desirable for accounting purposes, for separation of grades of plutonium, and to avoid mixing uranium streams of widely differing U^{235} contents.

In the case of such a requirement, it can be achieved at some cost in pond stock levels by segregation in the pond and by feeding the dissolver on a campaign basis, each campaign using a narrow band of feed stocks.

N. L. FRANKLIN,
Production Group U.K.AEA Risley.

CERAMICS—Thermal Conductivity

By G. ARTHUR, B.Sc., Ph.D. (*Ceramics Section, Parsons Nuclear Research Centre*

The role of ceramics in nuclear engineering is increasing in importance as greater use is made of them for fuels, moderators and structural materials. One of the most critical properties in nuclear applications is that of thermal conductivity and the various factors governing this are here examined and an indication given of the way in which it can be maximized.

THE main classes of ceramic materials are the metal oxides, carbides and nitrides. At present little is known of the silicides and borides. Compared with metals, ceramics are usually higher melting, stronger at high temperatures and more inert chemically. In some cases, notably UO_2 and UC, there is much improved radiation stability. The main disadvantage of ceramic materials is their lack of ductility which in conjunction with low thermal conductivity leads to poor thermal stress resistance.

The more important possible applications of ceramics in nuclear reactors are as fuels, moderators, controls and structural members. In the first three applications nuclear considerations are overriding in determining the selection of materials and the various ceramics available have been discussed at length elsewhere[1,2,3]. For structural materials, e.g. fuel carrying matrices and cans, low thermal neutron absorption cross-section, chemical stability and reasonably high melting point are essential. On this basis alone all primary oxides can be eliminated except BeO, MgO, Al_2O_3, ZrO_2. Of possible interest are TiO_2 and Cr_2O_3 but their cross sections are moderately high[4]. Binary and ternary compounds of the above oxides also exist but as discussed later these have lower thermal conductivities than the simple oxides and moreover are difficult to prepare in the dense form because of decomposition at high temperatures. Carbides and nitrides usually have higher thermal conductivity and better shock resistance than oxides but they suffer from the serious disadvantages of being difficult to fabricate to high densities and of having a low resistance to oxidation at high temperatures[5]. Silicon carbide and nitride are exceptions in that they are resistant to oxidation up to about 1 200°C due to the formation of a protective SiO_2 layer.

The X-ray densities, melting points and macroscopic thermal neutron absorption cross sections of compounds considered of possible interest in nuclear power production are listed in Table 1. Additional properties relevant to assessing a ceramic material for possible reactor use are thermal conductivity, thermal expansion, mechanical strength and resistance to irradiation damage. The thermal shock resistance is also of interest but as will be discussed in a later issue, this is a function of the primary properties listed above.

THERMAL CONDUCTIVITY

The thermal conductivity is one of the more important properties as this determines for a given heat flux the temperature gradients which will be produced. In most nuclear applications, e.g. fuel, matrix and can, to minimize these it is desirable that the thermal conductivity be as high as possible. Ceramic materials in general have a low intrinsic thermal conductivity but certain factors are known to effect a further lowering.

Heat can be conducted through a solid both by lattice vibrations and electron movement[26] so that:

$$K_T = K_L + K_e \qquad (1)$$

where K_T is the total thermal conductivity and K_L and K_e are the lattice and electronic components respectively. In metals, where there are a large number of free electrons, the lattice vibrations are largely damped by interaction with electrons so that the total thermal conductivity is given by K_e. By means of the kinetic theory it can be shown that for metals the ratio of the electronic thermal conductivity to the electrical conductivity is directly proportional to the absolute temperature.

$$K_e/\sigma T = \pi^2(k/e)^2/3 \qquad (2)$$
$$= 0.585 \times 10^{-8}\ \Omega \text{ cal cm/s°C}$$

where K_e = electronic thermal conductivity in cal/cm s°C
σ = electrical conductivity in $(\Omega\ \text{cm})^{-1}$,
k = Boltzmann constant,
and e = electronic charge.

This equation is known as the Wiedemann-Franz relation.

Table 1. Densities, melting points and thermal neutron cross-sections of some ceramic materials

Oxides	Density g/ml (by X-ray)	Melting point °C	Macroscopic cross-section[4] at 2 200 m/s cm²/ml
BeO	3·00[6]	2 450[7]	$0{\cdot}740\times10^{-3}$
MgO	3·58[6]	2 800[8]	$3{\cdot}260\times10^{-2}$
Al_2O_3	3·96[6]	2 050[8]	$10{\cdot}80\times10^{-2}$
SiO_2 (fused)	2·21[9]	1 713[9]	$3{\cdot}560\times10^{-2}$
ZrO_2 (cubic)	6·14[6]	2 680[10]	$5{\cdot}100\times10^{-3}$
TiO_2 (tetrag)	4·24[6]	1 840[8]	$185{\cdot}000\times10^{-3}$
Cr_2O_3	5·25[6]	2 280[8]	$128{\cdot}000\times10^{-3}$
MgO Al_2O_3	3·58[11]	2 130[8]	$7{\cdot}900\times10^{-3}$
2 MgO, 2 Al_2O_3, 5 SiO_2	2·77[11]	1 460[*8]	$5{\cdot}000\times10^{-3}$
2 Al_2O_3, 2 SiO_2	3·16[11]	1 810[*8]	$7{\cdot}600\times10^{-3}$
Sm_2O_3	7·20[6]	2 300[12]	139·000
Eu_2O_3	7·34[6]	2 050[12]	108·000
Gd_2O_3	7·65[6]	2 330[12]	1 171·000
Dy_2O_3	8·22[6]	2 340[12]	25·400
HfO_2	10·39[6]	2 780[13]	3·020
ThO_2	10·01[6]	3 300[14]	0·173
UO_2	10·96[6]	2 730[15]	0·188
PuO_2	11·46[15]	2 280[15]	239 (Pu^{239})

Carbides and nitrides	Density g/ml (by X-ray)	Melting point °C	Macroscopic cross-section[4] at 2 200 m/s cm²/ml
C (graphite)	2·27[6]	3 000[†16]	$0{\cdot}380\times10^{-3}$
Be_2C	2·44[6]	2 100[*17]	$1{\cdot}140\times10^{-3}$
SiC	3·21[18]	2 800[*19]	$7{\cdot}900\times10^{-3}$
TiC	4·90[6]	3 250[5]	$285{\cdot}000\times10^{-3}$
ZrC	6·66[6]	3 175[5]	$6{\cdot}840\times10^{-3}$
NbC	7·82[6]	3 500[5]	$52{\cdot}000\times10^{-3}$
Mo_2C	9·20[6]	2 690[5]	$147{\cdot}000\times10^{-3}$
Si_3N_4	3·20[20]	1 900[†17]	$110{\cdot}000\times10^{-3}$
ZrN	7·38[6]	2 980[5]	$86{\cdot}000\times10^{-3}$
NbN	8·39[6]	2 050[5]	$125{\cdot}000\times10^{-3}$
B_4C	2·52[6]	2 450[21]	82·400
HfC	12·70[6]	3 890[17]	4·240
BN	2·27[6]	3 000[17]	42·400
ThC	10·65[22]	2 625[22]	0·196
UC	13·62[22]	2 450[22]	0·252
PuC	13·65[22]	1 650[*24]	336 (Pu^{239})
ThN	11·56[6]	2 630[23]	0·267
UN	14·31[6]	2 650[23]	0·327
PuN	14·15[23]		346 (Pu^{239})
U_3Si	15·58[25]	960[*25]	0·293
U_3Si_2	12·20	1 665[25]	0·223

† Volatilizes. * Decomposes.

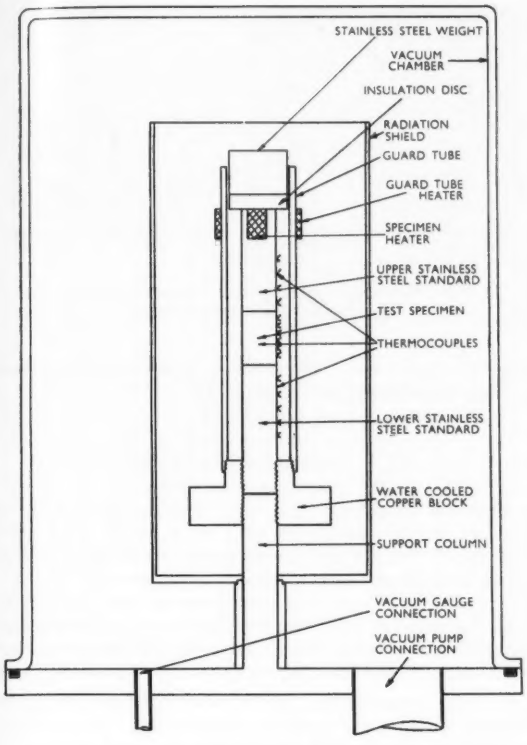


Fig. 1. Measurement of thermal conductivity by linear heat flow method.

In dielectric materials there are very few free electrons, even at high temperatures, so that the electronic component of the thermal conductivity is very small. Semiconductors occupy an intermediate position and will be discussed later. In normal ceramic materials the thermal conductivity is thus by lattice vibrations.

Lattice Conductivity

In the theory of lattice thermal conductivity developed by Peierls[27] the lattice vibrations have been quantised into phonons by analogy with the photons of electromagnetic vibrations and the concepts of the kinetic theory then applied. In this way it is shown that the thermal conductivity is given by:

$$K_L = cvl/3 \qquad (3)$$

where K_L is the lattice conductivity,
c is the specific heat of the material,
v is the mean velocity of phonons, approximately equal to the speed of sound,
and l is the mean free path of the phonons.

Above the Debye temperature (SiC, 230°C; BeO, 750°C; MgO, 600°C; UO_2, 600°C; ThO_2, 200°C) the specific heat and the mean phonon velocity are approximately constant so that the thermal conductivity is proportional to the phonon mean free path. If lattice vibrations were completely harmonic the phonon mean free path and therefore the thermal conductivity would be infinite. In a real lattice, however, the mean free path is reduced by various processes and it can be shown that the thermal resistances (the inverse of thermal conductivities) due to these various processes are additive, i.e.,

$$W_L = W_u + W_i + W_{im} + W_{vs} + W_{mb} + \text{etc.} \qquad (4)[28]$$

where W_L is the total lattice resistance and W_u, W_i, W_{im}, and W_{mb} are respectively the resistances due to anharmonic thermal vibrations (the " Umklapp " process of Peierls) isotopes, impurities, vacant lattice sites and mosaic boundaries. W_u is a fundamental property of a given crystal lattice and can be shown to vary above the Debye temperature directly as the absolute temperature. The resistances due to impurities and other irregularities are considered to vary only slightly with temperature provided the number of irregularities does not change with temperature. This has been confirmed experimentally in the case of impurities [29]. Equation (4) can therefore be simplified to:

$$W_L = aT + b. \qquad (5)$$

The contribution of the additional resistance b is thus proportionately greater in materials of high intrinsic conductivity and in any given material at low temperatures.

By inserting measured values of K_L, c and v in equation (3) values of l the phonon mean free path can be calculated. This has been done for a number of ceramic materials[30], the values obtained being between 30 and 100 Å for most ceramic materials at room temperature, decreasing to between 10 and 5 Å at 1 200°C. It is considered that the mean free path of the phonons cannot be reduced below the interatomic spacing (~ 5 Å) so that at high temperatures there is a lower limit to the value of the thermal conductivity.

In non-crystalline material such as glass the thermal conductivity is low and varies little with temperature[31]. The calculated mean free path in the case of fused silica[29] is approximately 5 Å which agrees closely with the interatomic spacing in the disordered silica network. It would thus appear that the network scatters phonons giving rise to a thermal resistance which is large compared to the other resistances.

When considering the thermal conductivity of different materials the theoretical approach gives a qualitative indication of the factors which influence the lattice conductivity, remembering that lattice symmetry favours high thermal conductivity. In ceramics, a compound with a simple structure with an anion—cation ratio of one, and with the anion and cation of approximately the same atomic weight, usually has a high thermal conductivity, e.g., BeO, MgO, and SiC. Compounds containing atoms with a high percentage of isotopes have usually a lower thermal conductivity. It has also been observed that compounds which are wholly ionic have a lower thermal conductivity than those in which the bond is partly covalent[26]. BeO has at room temperature a thermal conductivity several times that of MgO although MgO has a more symmetric crystal lattice and Mg and O are closer in atomic weight than Be and O. However, beryllium is wholly Be^9 whereas Mg has three isotopes. In addition there will be some covalency in the BeO bonding due to the small size of the Be++ ion.

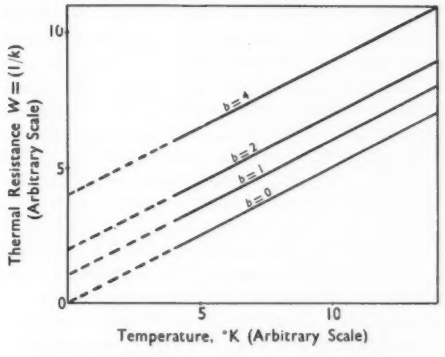


Fig. 2. Variation of thermal resistance with temperature and impurity content.

In several translucent ceramics, e.g., Al_2O_3, TiO_2 and MgO it has been observed that at high temperatures ($\sim$ 1 400°C for polycrystalline material) the thermal conductivity goes through a minimum and then increases slightly[32]. This increment in thermal conductivity varies as T^3 which would be expected if heat transfer were by radiation. In single crystal material, where the absorption is less, radiative heat transfer occurs at lower temperatures ($\sim$ 600°C). This effect has also been observed above 1 400°C in irradiated UO_2 containing large columnar grains[33].

Electronic Conduction

In the materials discussed so far, the thermal conductivity has been entirely by electrons (metals) or entirely by lattice vibrations (dielectrics). There is, however, a class of material in which both these mechanisms contribute to the thermal conductivity[34 35]. These elements are typified by a small number of conducting electrons so that lattice conduction is not completely eliminated by interaction with electrons. Examples of such materials are the elements of Group IV in which the first two Brillouin zones are completely filled but where the energy gap to the next unfilled zone is either zero (graphite) or small (silicon and germanium). The hard metal carbides and nitrides also fall into this category.

While it has not been conclusively shown that the Weidemann-Franz relation holds for semiconductors the evidence at present available[36 37] indicates that it is at least approximately true except in some unusual cases. Taking the values of Powell and Schofield[38] for the electrical resistivity and thermal conductivity of graphite the values of K_e and K_L shown in Table 2 are obtained. At low temperatures K_e is small but with increasing temperature it increases to approximately 50% of the total conductivity.

Table 2. Electrical resistivity and thermal conductivity of graphite

T, °C	Electrical Resistivity, (Ω cm)	Total Thermal Conductivity K_T, (c.g.s. units)	K_e	K_L, $(=K_T-K_e)$
0	$8{\cdot}2\times10^{-4}$	0·402	0·002	0·400
250	$6{\cdot}8\times10^{-4}$	0·290	0·005	0·285
700	$6{\cdot}8\times10^{-4}$	0·178	0·008	0·170
1 280	$7{\cdot}6\times10^{-4}$	0·100	0·011	0·089
2 000	$9{\cdot}6\times10^{-4}$	0·036	0·014	0·022
2 500	$10{\cdot}9\times10^{-4}$	0·029	0·015	0·014

The thermal conductivities of germanium and silicon have also been measured up to 400°C and the electronic contribution found to be small[34]. This is also true of the IV-IV compound silicon carbide; at 1 300°C, K_e is approximately 1×10^{-6} c.g.s. units[39], whereas the total thermal conductivity is 4×10^{-2} c.g.s. units[40].

Compounds containing a cation with an incompletely filled 3d or 4d electron shell can also develop a small number of free electrons at high temperatures[41]. Such ions can exist in more than one valency state and when two valency states are present the compounds become more conducting. For example, when TiO_2 is heated in a mildly reducing atmosphere there is a slight loss of oxygen, a corresponding reduction of Ti^{4+} to Ti^{3+} and the development of semi-conducting properties. In oxygen excess UO_2, some U^{6+} ions are present and similarly in UO_2 containing ions of lower valency (e.g., Y^{3+}) some U^{4+} ions are oxidized to U^{6+} to compensate for the lower charged addition. The number of conducting electrons in such compounds increases with temperature so that the electronic contribution to thermal conductivity is greater at high temperatures. The electrical conductivity of both non-stoichiometric ($UO_{2\cdot20}$)[42] and of yttria-doped UO_2[43] have been measured up to 600°C, the values obtained being of similar size. When these values are extrapolated to 2 000°C according to the equation:

$$\sigma = A\exp(-b/T) \qquad (6)$$

where σ = electrical conductivity,
T = absolute temperature,
and A and b are constants,

an electrical conductivity of approximately 20 $(\Omega\ \text{cm})^{-1}$ is obtained which corresponds to a value of $K_e = 2.3\times10^{-4}$ c.g.s. units. The thermal conductivity of undoped stoichiometric UO_2 at this temperature is approximately 40×10^{-4} c.g.s. units[44]. In the non-stoichiometric and yttria-doped oxide this value of the lattice conductivity would be reduced, due to increased scattering by impurities, so that an increase in the total thermal conductivity (K_L+K_e) would be unlikely.

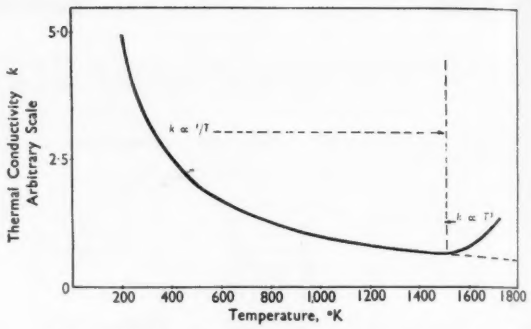


Fig. 3—General relationship between thermal conductivity and temperature.

At lower temperatures the ratio of K_e to the total conductivity would be even smaller as the number of conducting electrons would be less (equation 6), their efficacy in conducting heat lower (equation 2) and the lattice conductivity higher (equation 5).

Macroscopic Effects

In addition to the atomic mechanisms discussed above there are macroscopic factors, e.g., porosity and second phases, which affect the thermal conductivity. The effect of porosity on the thermal conductivity has been analysed by Euken[45] and, more recently, by Loeb[46]. The two approaches give slightly different results and the experimental work of Francl and Kingery[47] on material containing isometric pores agrees closely with the formula of Loeb:

$$K = K_o(1-P) \qquad (7)$$

where K_o and K are respectively the thermal conductivities of completely dense material and material containing a fractional porosity P. Material containing 10% porosity has thus a thermal conductivity 10% lower than material without porosity.

The effect of a second phase on the thermal conductivity has also been analysed by Euken[45] and investigated experimentally by Kingery[29]. Euken obtained the formula:

$$K_T = k_1\left[\frac{1-(1-Ak_2/k_1)V_2}{1+(A-1)V_2}\right] \qquad (8)$$

where $A = 3k_1/(2k_1+k_2)$.

K_T is the overall thermal conductivity of a material consisting of a dispersion of a material of conductivity k_2 (fractional volume concentration V_2) in a material of thermal conductivity k_1. For a dispersion of spherical particles the formula is accurate up to approximately 50 vol. % of the dispersed phase. At higher concentrations the formula has not been tested experimentally because of the difficulties in obtaining a true dispersion. If the matrix is the higher conducting phase then the formula will give a higher value of thermal conductivity than is actually obtained in practice. Table 3 gives the calculated thermal conductivities of a

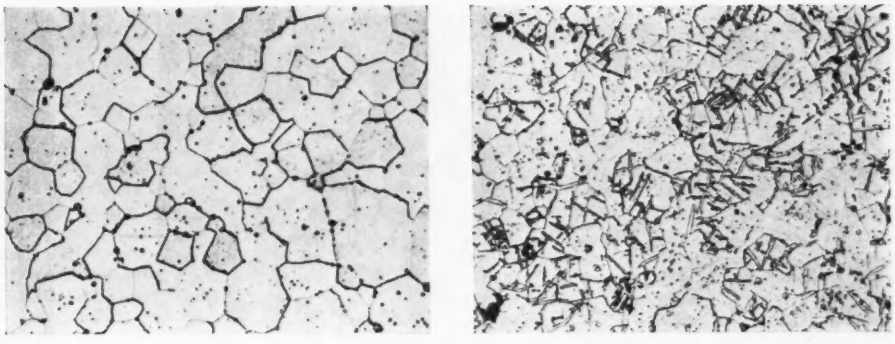


Fig. 4—Photomicrographs of stoichiometric (left) and non-stoichiometric (right) UO_2. The photograph on the right shows needles of U_4O_9 precipitate.

Table 3. Conductivity as a function of dispersion

Vol. % of high conductivity matrix	K_T, A in B	K_T, A in C
50	0·094	0·171
30	0·074	0·106
10	0·031	0·047
1	0·021	0·023

Table 4. Thermal conductivity of Al_2O_3 containing Cr_2O_3

T	W/o Cr_2O_3				
	0	0·4	1·70	3·86	8·50
100°C	0·072	0·064	0·052	0·046	0·039
200°C	0·052	0·046	0·040	0·037	0·031
400°C	0·031	0·028	0·026	0·024	0·020
800°C	0·019	0·016	0·015	0·013	0·012
1 000°C	0·015	0·013	0·012	0·012	0·011

dispersion of a low conductivity material (A) ($k_A = 0.02$) in various amounts of materials B and C of higher conductivities ($k_B = 0.2$, $k_c = 0.4$).

Increasing Thermal Conductivity

To obtain the maximum lattice conductivity, the resistances due to impurities and other defects should be a minimum. In normal ceramics where the grain size is of the order of 5μm or greater, i.e., many times the phonon mean free path, the contribution of grain boundaries to the thermal resistance is small[32]. The effect of impurities has, however, been observed in several cases even when the impurity concentration was small and the temperature high[29 32]. In alumina containing various percentages of chromium oxide in solid solution the thermal conductivity was lowered considerably[29], the decrease being proportional to the impurity concentration (Table 4).

In the case of uranium oxide under irradiation it has been observed that oxide of high purity had a thermal conductivity approximately 15% higher than oxide of lower purity[48].

To obtain the maximum thermal conductivity the number and weight of isotopes should also be kept to a minimum. It would be expected that the thermal conductivity of enriched UO_2 would be smaller than natural. However, the effect should not be large because of the small mass difference between U^{235} and U^{238}.

In oxides of the transition and actinide metals (e.g., UO_2) there is the possibility that the electronic component of the conductivity could be increased sufficiently to raise the total conductivity a significant amount but with the information presently available this seems unlikely.

The highest conductivity is obtained in material of highest density (equation 7), so that the porosity should be reduced to a minimum. High density material will also have a lower absorption at high temperatures so that heat transfer by radiation should also be greater.

The addition of a high conducting material which did not go into solution but which formed a continuous network would also raise the conductivity, whereas if it remained as discrete particles its influence would be small.

Table 5. Thermal conductivity values, 10^{-3} cal/cm s°C

Material	25°C	200	400	600	1 000	1 400		References
BeO	48·0 (100°C)	34·0	20·0	13·0	7·0	4·5	3·6 (1 700)	49, 50, 51, 52, 53
MgO	11·0	8·0	4·5	3·0	1·6	1·5	2·2 (1 800)	32, 50, 51, 54
Al_2O_3	9·2	5·2	3·1	2·2	1·5	1·4	1·8 (1 800)	32, 51, 54, 55, 56
SiO_2 (fused)	0·35	0·40	0·45	0·60	—	—	—	30
TiO_2	2·5*	1·80	1·21	0·92	0·80	—	—	32
$Zr^{-}O_2$	0·47	0·47	0·49	0·50	0·55	0·58	—	50
MgO Al_2O_3	4·3*	3·1	2·4	1·9	1·4	—	—	57
$3Al_2O_3$ $2SiO_2$	1·7	1·3	1·1	1·0	1·0	0·9	—	57
Graphite (nuclear)	48·0	36·0	29·0	23·0	17·0	11·5	9·0 (2 000)	58, 59
Graphite (structural)	16·0	14·5	13·0	11·5	9·0	—	Longitudinal (transverse 60%)	60
Be_2C	—	0·28*	0·34	0·42	0·56*	—	—	61
SiC (hot pressed)	16·0	11·8	9·2	7·3	5·0	—	—	45, 40, 62
SiC (siliconised)	27·0	21·4	17·3	13·8	10·0	—	—	62
TiC (hot pressed)	7·3	5·3	3·5	2·1	1·3	—	—	40
ZrC	4·9	—	—	—	—	—	—	21
ZrN	6·5	4·1	2·6	1·8	1·6	—	—	40
Si_3N_4	0·54	—	—	—	—	—	—	20
B_4C	6·7 (100)	6·0	4·8	4·1	2·6*	Values at right angles approx. half those quoted		64
BN	—	7·0	6·8	6·6	6·4			
ThO_2	3·60*	2·23	1·39	1·02	0·71	—	—	50
UO_2	2·34 (100)	1·90	1·38	1·06	0·82	0·66		44, 57, 65
	1·68 (100)	1·33	1·02	0·82	0·57	0·48	0·44 (1 600)	66
$UO_{2.18}$	0·78 (100)	—	—	—	—	—	—	29
UC	6·5	5·6	5·1	4·9	4·8	—	—	22
U_3Si	3·6	—	—	—	—	—	—	67
U_3Si_2	3·5	—	—	—	—	—	—	67

* Extrapolated

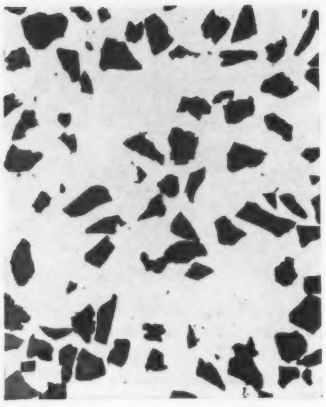


Fig. 5 (a).—30 w/o UO_2 70 w/o stainless steel % of theoretical density= 99.0. Magnification × 25.

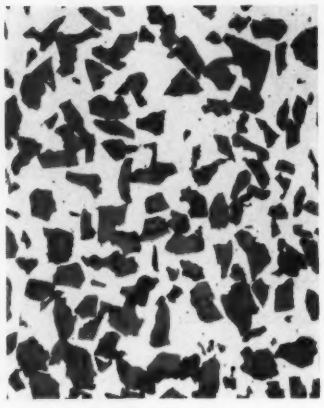


Fig. 5 (b).—55 w/o UO_2 45 w/o stainless steel % of theoretical density= 96.8. Magnification × 25.

Fig. 5 (c).—70 w/o UO_2 30 w/o stainless steel % of theoretical density= 95.5. Magnification × 25.

Values of Thermal Conductivity

Values of the thermal conductivity of materials which are or may be of interest in reactor technology are listed in Table 5. No values have been found for materials which are given in Table 1, but which do not appear in Table 2. The values, except those for graphite, have been corrected to zero porosity according to equation (7). As there is at present no method by which graphite can be prepared to high densities (> 80% theoretical) it was thought unrealistic to adjust the measured values in this case.

A considerable variation was found in the values for BeO below 400°C in the various investigations. Above 400°C the agreement is reasonably good. The average values have been listed. It is interesting to note that it is in such high conductivity materials as beryllia and at low temperatures that the effect of impurities and other crystal defects (term b in equation 5) would be expected to have the greatest effect.

The values of MgO and Al_2O_3 from the various sources are in reasonably close agreement.

There is a wide variation in the thermal conductivities of various graphites depending on the degree of graphitization and on the amount of preferred orientation of the crystallites so that the values for two graphites have been given. The first values are for a nuclear graphite of high conductivity and with a relatively small amount of preferred orientation while the other values are for a highly orientated, low conductivity structural graphite. The values given for this latter material have been measured parallel to the direction of extrusion. Measured at right angles to the extrusion direction the conductivity is approximately 60% of that given.

Boron nitride has a layer structure similar to graphite and consequently the thermal conductivity shows a similar directional dependence.

Two sets of values are listed for silicon carbide; the first is for pure silicon carbide and is the result of three investigations which show remarkable agreement considering the different routes followed. Euken[45] deduced the thermal conductivity of silicon carbide crystals from the thermal conductivities of several bricks containing varying amounts of silicon carbide, silicate glass and pores. Vasilos and Kingery[39] measured the conductivity directly on material taken from a commercial silicon carbide furnace whereas the third investigation[62] used a sample hot pressed from β silicon carbide powder. The second set of results is for material containing approximately 4 w/o silicon. The values given for the thermal conductivity of this material are much higher than would be predicted from equation (8). An explanation of this discrepancy cannot at present be given.

There is considerable divergence in the values for UO_2; the highest and lowest values found in the literature have been quoted. It was formerly supposed that the values of Hedge and Fieldhouse[44] were low because extensive cracking had occurred during measurement. However, a more recent measurement is in good agreement with these low values[65]. A fourth investigation has found that material prepared by the low temperature non-stoichiometric sintering route and subsequently reduced had a thermal conductivity in fair agreement with Hedge and Fieldhouse, whereas material sintered in hydrogen at 1 750°C gave results in fair agreement with Kingery's values[66]. Earlier irradiation work[68] was in agreement with the values of Hedge and Fieldhouse whereas more recent irradiation work[48] favours Kingery's values. The discrepancy may be due to the presence of a small amount of non-stoichiometric oxygen or some other impurities in the low conductivity materials.

REFERENCES

1. Epremian, E. "Uranium Compounds for New High Temperature Fuels." Fuel Elements Conference, Paris, 1957.
2. Wisnyi, L. G. "Ceramics in Nuclear Reactors." *Ceramic Industry* 74, 2, 3 and 4, 1960.
3. Murray, P. and Williams, J. "Ceramic and Cermet Fuels." A./Conf. 15/P. 318, Geneva, 1958.
4. Hughes, D. J. and Schwartz, R. B. "Neutron Cross Sections." B.N.L. 325, 1958.
5. Schwartzkopf, P. and Kieffer, R. "Refractory Hard Metals." Macmillan, New York, 1953.
6. Pearson, W. B. "Lattice Spacings and Structures of Metals and Alloys." Pergamon Press, 1958.
7. Engberg, C. J. and Zehms, E. H. "Thermal Expansion of BeO, MgO, B_4C, SiC and TiC above 1 000°C." *Jnl. Amer. Cer. Soc.* **42**, 6, 1959.
8. Levin, E. M. *et al.* "Phase Diagrams for Ceramists." Amer. Cer. Soc., 1956.
9. Thermal Syndicate Co., Ltd. Technical Bulletin on Fused Quartz and Silica, 1951.
10. Brown, F. H. and Duwez, P. "The Systems Zirconia-lanthana and Zirconia-neodymia. *Jnl. Amer. Cer. Soc.* **38**, 3, 1955.
11. Rigby, G. R. "Thin Section Mineralogy of Ceramic Materials." Brit. Cer. Res. Assn., 1953.
12. Ploetz, G. L. *et al.* "Sintering Characteristics of Rare Earth Oxides." *Jnl. Amer. Cer. Soc.*, **41**, 12, 1958.
13. Rossini, F. D. *et al.* "Selected Values of Thermodynamic Properties." *Circ. Natl. Bur. Stnds.*, 500, 1952.
14. Lambertson, W. A. *et al.* "Uranium Oxide Phase Equilibrium Systems, IV, UO_2–ThO_2." *Jnl. Amer. Cer. Soc.*, **36**, 12, 1953.
15. Chikalla, T. D. "Studies of the Oxides of Plutonium." Conference International sur la métallurgie du Plutonium, Grenoble, 1960.
16. Ubbelohde, A. R. and Lewis, F. A. "Graphite and its Crystal Compounds." Oxford University Press, 1960.
17. Quill, L. L. "Chemistry and Metallurgy of Miscellaneous Materials." McGraw-Hill, 1950.
18. Taylor, A. and Laidler, D. S. "Formation and Crystal Structures of Silicon Carbide." *Brit. Jnl. Appl. Phys.*, **1**, 7, 1950.
19. Scace, R. I. and Slack, G. A. "The Si–C and Ge–C Phase Diagrams." "Silicon Carbide," Pergamon Press, 1960.
20. Ingles, T. A. *et al.* 9th Interim Report, Brit. Cer. Res. Assn., 1958.
21. Campbell, I. E. "High Temperature Technology." Wiley, New York, 1957.
22. Rough, F. A. and Chubb, W. C. "An Evaluation of Nuclear Carbides." B.M.I., 1441, 1960.

The SRE Breakdown and the New Core

by R. W. DICKINSON,
(*Director, AI Sodium Reactor Dept.*)

THE Sodium Reactor Experiment (SRE) at Santa Susana, which was shut down in July, 1959, following the discovery of damage to 12 of its 43 fuel elements, is now back in operation. Criticality with a second core loading of thorium-uranium metal fuel was achieved in September, 1960; since then a carefully planned series of experiments designed to establish the physics parameters and stability of the new fuel material have been carried out to test its stability under full power operation at 20 MW(th).

Damage in the original core has been definitely ascribed to interference with fuel element heat transfer, which was created by the deposition of decomposition of an auxiliary coolant (tetralin). Some 10 gal of this coolant was introduced through a leaking thermocouple well in the main primary pump freeze seal gland; amorphous carbon and hydrocarbons plugged the entry portions of damaged fuel channels, and "plated" out on high heat transfer areas of fuel elements. Resulting high local temperatures on the fuel elements caused excessive swelling of the unalloyed uranium fuel, splitting the 0·010 in thick tubular cladding in some instances, and forming iron-uranium eutectic (molten at 1 430°F) in others. In all, 10 fuel elements had each of their seven component rods severed just below the midplane, two elements were stuck in their moderator cans, and one suffered only minor damage to cladding.

Recovery operations involved the remote removal of 83 fuel slugs from the core, maintaining both an inert atmosphere (argon) and a temperature higher than 250°F in the core at all times. Eighty-one slugs 6 in long and ¾ in in diameter, along with smaller bits of cladding were recovered from the top of the core, and two slugs were recovered from the bottom plenum. The difficulty of this last operation can be appreciated when it is recognized that the lower plenum is 33 feet below the loading face, where manipulators and optics were placed, and is accessible only through 2 in dia. holes in the lower grid plate. A total of 16 moderator cans, of the 119 installed, were replaced with new cans. Twelve of these cans contained damaged fuel elements; the operation was performed using shielded casks and grapples designed and built after the damage was incurred. Thirteen cans were initially replaced; three more were discovered to have been damaged by grappling operations and were later replaced.

Recovery operations were notable in that they were performed by the regular operating and maintenance crews, none of whom was over-exposed to radiation. All fission products except the noble gases appeared to be retained in the primary sodium; they are now being removed with apparent effectiveness by the cold trap. The mechanism of removal is not yet clearly understood, but the carbon present is apparently assisting fission removal, perhaps in conjunction with oxygen.

The new core, made up of 40 5-rod clusters of thorium 7·6w/o, 93% enriched uranium, contains 1 144 kg of thorium and 94 kg of uranium. Maximum central fuel temperature will be limited to 1 200°F at 20 MW(th) operation; as irradiation experience is acquired the propriety of increasing this temperature (and power level) will be examined. The 11 in triangular lattice has been preserved, and core configuration is identical with the original core except for three fuel elements, for which zirconium clad graphite cylinders have been substituted to preserve sodium flow characteristics.

Organic coolants have been removed from the reactor system except where at least two barriers exist between coolant and sodium. NaK cooled freeze seals have been installed in all pumps, and ambient atmosphere cooled freeze seals were placed on the main coolant system valves in place of tetralin cooled freeze seals. Numerous other system and component revisions were made to eliminate the possibility of sodium contamination. The measures taken are confidently expected to provide regular operation of this important experiment, which in addition to providing the U.S.AEC, sponsors of the project, and Atomics International, designer and operator, with considerable useful information, will continue to be used for the generation of electricity by the Southern California Edison Company.

Continued from previous page

23. Chiotti, P. "Experimental Refractory Bodies of High Melting Nitrides, Carbides and Uranium Dioxide." *Jnl. Amer. Cer. Soc.* **35**, 5, 1952.
24. Mulford, R. N. R. *et al.* "The Plutonium Carbon System." Conference International sur la Métallurgie du Plutonium, Grenoble, 1960.
25. Rough, F. A. and Bauer, A. A. "Constitution of Uranium and Thorium Alloys." B.M.I., 1300, 1958.
26. Ziman, J. M. "Electrons and Phonons." Oxford University Press, 1960.
27. Peierls, R. *Ann. Phys.* **5**, 3, 1929.
28. Klemens, P. G. "The Thermal Conductivity of Dielectric Solids at Low Temperatures." *Proc. Roy. Soc.*, 208A, 1951.
29. Kingery, W. D. "Thermal Conductivity XIV Conductivity of Multi-component Systems." *Jnl. Amer. Cer. Soc.* **42**, 12, 1959.
30. Kingery, W. D. "Thermal Conductivity XII Temperature Dependence of Conductivity for Single Phase Ceramics." *Jnl. Amer. Cer. Soc.* **38**, 7, 1955.
31. Kittel, C. "Interpretation of the Thermal Conductivity of Glasses." *Phys. Rev.* **75**, 6, 1949.
32. Charvat, F. R. and Kingery, W. D. "Thermal Conductivity XIII Effect of Microstructure on the Conductivity of Single Phase Ceramics." *Jnl. Amer. Cer. Soc.* **40**, 9, 1957.
33. Bates, J. L. "Thermal Conductivity of UO_2 at High Temperatures." H.W., 64626, 1960.
34. Stuckes, A. D. On the Thermal Conductivity of Semi-conductors. *Phil. Mag.* **5**, 49, 1960.
35. Tennery, V. J. "Review of Thermal Conductivity and Heat Transfer in Uranium Dioxide." ORNL, 2656, 1959.
36. Price, P. J. *Phys. Rev.* **95**, 596, 1952.
37. Thullier, J. M. *Compt. Rend.* **241**, 1121, 1955.
38. Powell, R. W. and Schofield, F. H. "Thermal and Electrical Conductivity of Carbon and Graphite." *Proc. Phys. Soc.* **51**, (1), 283, 1939.
39. Pohl, R. G. "Electrical Properties of Silicon Carbide." "Silicon Carbide." Pergamon Press, 1960.
40. Vasilos, T. and Kingery, W. D. "Thermal Conductivity XII Conductivity of Some Refractory Carbides and Nitrides." *Jnl. Amer. Cer. Soc.* **37**, 9, 1954.
41. Hannay, N. B. "Semi-conductors." Reinhold Publishing Corporation, New York, 1959.
42. Willardson, R. K. *et al.* "The Electrical Properties of Uranium Oxides." *Inorganic and Nuclear Chemistry* **6**, 1, 1958.
43. "Thermoelectric Nuclear Fuel Element." Annual Progress Report, 1959, WCAP, 1162.
44. Hedge, J. C. and Fieldhouse, J. B. "Measurement of Thermal Conductivity of Uranium Oxide." AECU, 338, 1956.
45. Euken, A. "Thermal Conductivity of Ceramic Refractory Materials; its Calculation from Thermal Conductivity of Constituents." *Forsch. Gebiete Ingenieurw.* **3**, 353, 1932.
46. Loeb, A. L. "Thermal Conductivity (VII) a Theory of Thermal Conductivity of Porous Materials." *Jnl. Amer. Cer. Soc.* **37**, 2, 1954.
47. Francl, J. and Kingery, W. D. "Thermal Conductivity (IX) Experimental Investigation of Effect of Porosity on Thermal Conductivity." *Jnl. Amer. Cer. Soc.* **37**, 2, 1954.
48. Cohen, J. *et al.* "Measurement of the Thermal Conductivity of Metal Clad Uranium Oxide Rods During Irradiation." WAPD, 228, 1960.
49. Wood, W. D. *et al.* BMI, 1448 (rev.), 1960.
50. Adams, M. "Thermal Conductivity (III) Data for Al_2O_3, BeO, MgO, ThO_2 and ZrO_2." *Jnl. Amer. Cer. Soc.* **37**, 2, 1954.
51. Francl, J. and Kingery, W. D. "Thermal Conductivity (IV) Apparatus for Determining Thermal Conductivity by a Comparative Method; Data for Pb, Al_2O_3, BeO and MgO." *Jnl. Amer. Cer. Soc.* **37**, 2, 1954.
52. Taylor, R. E. "Thermal Conductivity and Thermal Expansion of BeO at Elevated Temperatures." NAA–SR–4905, 1960.
53. "Background Information on Beryllia as a Moderator." G.A., 1280, 1960.
54. McQuarrie, M. "Thermal Conductivity (V) High Temperature Method and Results for Al_2O_3, MgO, BeO." *Jnl. Amer. Cer. Soc.* **37**, 2, 1954.
55. McClelland, J. D. and Zehms, E. H. "Thermal Conductivity of MgO from 1 030°C to 1 880°C." *Jnl. Amer. Cer. Soc.* **43**, 1, 1960.
56. Sutton, W. H. "Apparatus for measuring the Thermal Conductivity of Ceramic Materials." *Jnl. Amer. Cer. Soc.* **43**, 2, 1960.
57. Kingery, W. D. *et al.* "Thermal Conductivity (X) Data for Several Pure Oxides." *Jnl. Amer. Cer. Soc.* **37**, 2, 1954.
58. Eatherby, W. P. *et al.* "Physical Properties of Graphite for Special Nuclear Applications." A/Conf. 7 P 708, Geneva, 1958.
59. Wagner, P. *et al.* "Some Mechanical Properties of Graphite in the Temperature Range 20°–3 000°C." A/Conf. 7, P 702, Geneva, 1958.
60. Ford, A. R. *et al.* "The Properties of E.Y. 9 Electrographite." OEEC Graphite Symposium, Winfrith, 1959.
61. Neely, J. L. *et al.* "Thermal Conductivity and Heat Capacity of Be_2C." *Jnl. Amer. Cer. Soc.* **33**, 12, 1950.
62. Alliegro, R. A. *et al.* "Pressure Sintered Silicon Carbide." *Jnl. Amer. Cer. Soc.* **39**, 11, 1956.
63. Carborundum Co. Technical Bulletin on K.T. Silicon Carbide, 1956.
64. Ingles, T. A. and Popper, P. "Boron Nitride I." Brit. Cer. Assn., Paper 398, 1958.
65. Lucks, C. F. and Deem, H. W. B.M.I., 1448 (rev.), 1960.
66. Seddon, B. J. "Uranium Ceramics Data Manual." U.K.AEA, D.E.G. Report 120 (R), 1960.
67. Nichols, R. W. "Ceramic Fuels, Properties and Technology." *Nuclear Engineering* **3**, 29, 1958.
68. Robertson, J. A. L. *et al.* "Behaviour of Uranium Oxide as a Reactor Fuel." A/Conf. 6, P 193, Geneva, 1958.

The Improvement of Fuel Element Heat Transfer by Surface Roughening

By V. WALKER

(Research Manager, Heat Transfer, Windscale; D & E Group, U.K.AEA)

EXPERIMENTAL work on heat transfer from roughened surfaces was started at Windscale about five years ago with broad ideas about the potential applications of roughened surfaces to fuel elements, ideas which later developments have shown to be sound. Most important was the belief that secondary surfaces would seriously decline in value owing to falling fin efficiency with the trend to more highly rated gas-cooled reactors.

The fin efficiency of a Calder can in the centre channels of the reactor is rather less than 70% and the fins on the polyzonal cans for the civil reactors probably have about the same efficiency, increases in rating since Calder having been compensated by the use of shorter and tapered fins. (Fin efficiency is defined in the usual way as the ratio of the heat transferred by the fin to that which would be transferred by a fin of infinite thermal conductivity with the same base temperature and identical coolant flow conditions.) It does not necessarily follow that uranium-magnox fuel elements with substantially increased heat ratings would have appreciably lower fin efficiencies. If the fuel were then divided up into smaller diameter rods, a necessary step in any case to avoid excessive centre uranium temperatures, a satisfactory arrangement could probably be achieved using shorter fins in conjunction with the increased primary surface area. Therefore not only is there no indication of a limit based on declining efficiency to the use of fins on uranium-magnox fuel elements but also there is no suggestion that roughened surfaces could compete on heat transfer performance with finned magnox cans.

However, the situation is very different when canning materials other than magnesium alloy are introduced to achieve higher temperature operation. The following factors all point to a decline in interest in fins:—

(1) The low thermal conductivity of stainless steel and similar high temperature materials—a factor of six or seven down on magnox—leading to very inefficient fins.

(2) The difficulty of fabricating beryllium in complex shapes.

(3) The need to minimize the quantities of stainless steel owing to its high neutron absorption, and of beryllium owing to its cost.

If fins are not to be used, the fuel must be subdivided to give a large primary surface resulting, for example, in the rod cluster fuel elements for the Windscale AGR. It is desirable for several reasons to minimize the primary surface area; increasing heat transfer coefficients by surface roughening appeared to be a possible means of doing this. References in the literature to the effects of deliberate roughening on heat transfer were very limited and were not encouraging, tending to conclude that the increases in pressure drop, caused by wasteful form drag on the roughness elements, were prohibitive compared with the improvement in the heat transfer coefficient. This conclusion was treated with some reserve, not only because the range of roughened surfaces investigated had been small but also because the basis used for the comparison with smooth surfaces had necessarily been incomplete. A proper comparison needs to be made within a particular context taking into account the side effects in addition to the direct effect on heat transfer performance. The economic advantage of using roughened surfaces might not arise from an improved reactor thermal performance but from a reduction in the amount of canning material or a cheapening of fuel element production. It was decided to undertake a basic investigation of heat transfer and friction for surfaces having various sizes and shapes of roughness, to be followed by an examination of their potential applications to highly rated gas-cooled reactor fuel elements.

Experimental Procedure

The apparatus was very straightforward, consisting of a roughened circular rod about 2 in in diameter located by streamlined supports along the axis of a smooth, externally insulated circular channel with an internal diameter of 3·5 in. The aluminium channel was 14 ft long for the bulk of the experiments and was provided with static pressure tappings, in groups of three, every 6 in along its length. The roughened rod was also made from aluminium in 13 sections each 1 ft long, heat being generated inside them by passing low voltage alternating current through a stainless steel tube insulated from the aluminium elements by a glass silk sleeve. A number of voltage tappings brazed into

NOMENCLATURE

r	Radius; suffix 1 refers to radius of rough surface, suffix 2 to the channel radius, and m to the radius of maximum velocity
u	Point coolant velocity
ε	Height of roughness
p	Pitch of roughness
d_e	Equivalent diameter of annular region between rough surface and surface of no shear; equivalent diameter of cluster
St	Stanton number; suffix s refers to value for smooth surface
f	Friction factor defined by Guggenheim equation; suffix s refers to value for smooth surface
θ	Temperature; suffixes 1 and 2 refer to channel inlet and outlet coolant temperatures respectively and suffix Sm to the nominal maximum rod surface temperature
L	Length of fuel in channel
L'	Extrapolated length
β	Ratio of maximum to average flux in channel
A	Flow area
S_H	Element perimeter
Δp	Coolant pressure loss
$\bar{p}$	Mean coolant pressure
n	Number of rods in cluster
N	Number of rods in channel
d	Fuel rod diameter
W	Coolant mass flow rate
Q	Channel heat output

the heater tube wall and led out along the inside determined the voltage gradient and hence the heat generation rate. Air at substantially atmospheric pressure was blown through the channel at flow rates up to 1 lb/s measured by an orifice plate. The temperatures of the roughened elements were measured at 26 positions by chromel-alumel thermocouples inserted into 2 in deep axial holes located $\frac{1}{8}$ in below the curved surface at both ends of each 1 ft section and, to minimize flow disturbances, all thermocouple leads were brought out axially in a $\frac{1}{16}$ in wide slot extending along the 13 elements. The thickness and high thermal conductivity of the aluminium elements would of course eliminate both circumferential temperature variations and short-range axial variations associated with an intermittent type of roughness such as isolated ribs. (Later tests using thin steel tubes with an isolated rib type roughness have revealed small periodic temperature variations with period equal to the pitch of the ribs.) The principal measurements were taken from a 4 ft long test section starting 6·75 ft from the channel entry, temperature distribution measurements having shown that the surface to gas temperature difference had by then become sensibly constant.

Temperature and static pressure measurements were made for various heat generation rates up to 2 kW/ft and indeed the whole apparatus and procedure were very similar to those used on fuel element can heat transfer work. An additional feature of these tests, however, was that coolant velocity and temperature distribution measurements were made as a routine part of each test by traversing radially across the annulus between the rough surface and the smooth wall of the channel a combined total head tube and thermocouple. These last measurements played a very important part in the analysis and presentation of the results.

Presentation of Experimental Results

There were sound reasons for the choice of a simple experimental arrangement for the comparison of different roughened surfaces. However, the problem arose of predicting with reasonable accuracy the performance of various arrangements of fuel elements with roughened surfaces. It becomes obvious that some correction to the experimental results is necessary if one supposes that the roughened rod is small in diameter compared with the smooth channel. Owing to the relatively large amount of smooth channel surface the friction factor for the whole system would be little affected by roughening the rod, whereas heat transfer from the rod might be considerably improved. It would therefore be misleading to quote average Stanton numbers and friction factors obtained from the Windscale apparatus and apply them to reactor fuel elements in which most of the surface is roughened.

In applying the roughened surface data to fuel element systems two distinct problems arise:—

(a) The passage shapes are different.

(b) The proportions of rough (and heated) and smooth (unheated) surface area are different.

A method of dealing with this situation was advanced by W. B. Hall, who initiated all the Windscale work on roughened surfaces, and the following description is largely taken from his paper[1].

The proposed method, does not make full allowance for the difference between experimental system and fuel element; rather, it attempts to reduce the experimental results to a form in which they are directly comparable with a system having the whole of the surface heated and roughened (e.g., a tube with internal flow). The equivalent diameter concept is then invoked to allow for differences

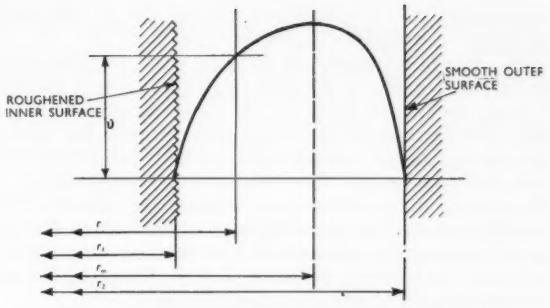


Fig. 1.—Velocity distribution across annular passage.

in shape and the results can be directly applied to, for example, an infinite array of rods in longitudinal flow. Allowance must then be made for the fact that in a fuel element the array of rods is finite and is surrounded by a smooth channel wall; as described later in this article it has in fact been found possible to make such an allowance.

In the course of the heat transfer experiments, the velocity and temperature distributions across the annulus are measured; the approximate shapes of these are shown in Figs. 1 and 2. The steps in the transformation applied to these distributions are given below, the aim being to isolate the rough surface from the smooth in so far as heat transfer and drag are concerned.

(a) From the velocity distribution (Fig. 1) the radius r_m at which $du/dr = O$ is determined and this radius defines a cylindrical surface at which there is no shear stress.

(b) By applying a force balance on the region of the annular passage between the inner radius, r_1, and the radius of no shear, r_m, the drag on the rough inner surface of the passage can be calculated and a friction factor defined for the system of rough surface plus associated flow passage (i.e., that part of the passage between r_1 and r_m).

(c) Similarly a Reynolds number can be defined for the above system of rough surface and flow passage (between r_1 and r_m). The assumption is then made that the resulting friction factor-Reynolds number relationship is identical with that which would exist for a circular passage having the same relative roughness (i.e., same ratio of roughness size to effective diameter). The justification here is that in both systems the whole of the surface of the passage is roughened; the imaginary surface of the radius r_m in the experimental system is ignored in calculating the effective diameter of the flow passage since there is no drag on it. Clearly there is a difference in the shape of the

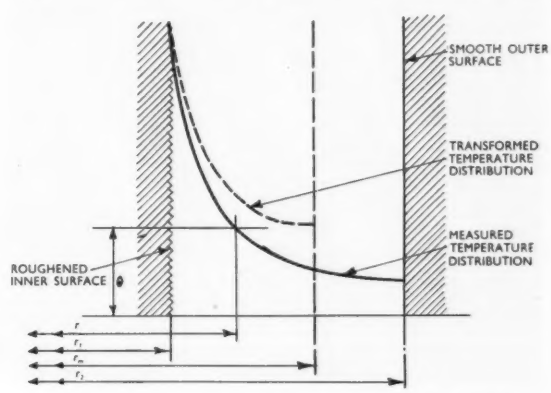


Fig. 2.—Temperature distribution across annular passage.

two systems, and it is assumed that the use of "effective diameter" satisfactorily allows for this.

(d) The heat transfer results must also be transformed so that they apply to a system analogous to that used in defining the friction factor for the rough surface. The first step here is to adjust the temperature distribution across the passage so that it is analogous to the velocity distribution; this requires that there should be no heat transfer at the surface of no momentum transfer (or shear). This modification can be made with reasonable accuracy using the experimentally determined distributions of velocity and eddy conductivity between r_1 and r_m. The transformed temperature distribution is shown in Fig. 2.

(e) Using the new temperature distribution a new bulk mean fluid temperature and a new temperature difference (surface temperature—bulk mean fluid temperature) can be calculated. Since the heat flux at the rough surface is maintained constant in the transformation, the new heat transfer coefficient is obtained by multiplying the old value by the ratio of old temperature difference to new temperature difference. A new Stanton number can then be obtained for the transformed system. Using the same arguments as were applied to the friction factor this Stanton number can then be applied directly to any other system having the whole of the surface both roughened and used for heat transfer.

An important assumption underlying this transformation is that the distributions of eddy conductivity and viscosity between r_1 and r_m are independent of what happens beyond r_m, e.g., they would be unchanged if, instead of a smooth surface at r_2, the outer boundary had been a second roughened surface located at some radius greater than r_2 to give the same radius of no shear. This is a reasonable assumption as it is the eddy viscosity and conductivity close to the roughened surface that are of particular importance. Although this transformation has not been extensively tested by experiment, predictions of roughened rod cluster pressure loss have proved to be remarkably accurate.

The numerical work involved in making the transformation was initially done using a desk machine but was later programmed for a Ferranti Mercury digital computer.

Experimental Results

The surfaces studied have covered a fairly wide range of different shapes and sizes of roughness including Whitworth screw threads, square threads, sine waves, circular wires wound on a smooth rod, and a range of circumferential ribs. The ribs, a selection of which is shown in Fig. 3, have

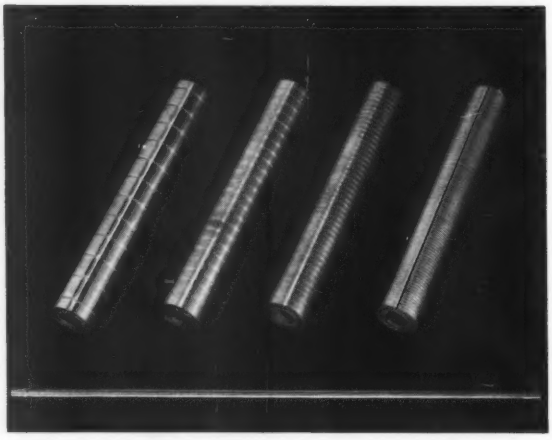


Fig. 3.—Experimental elements and a typical roughened can.

TABLE 1. Rib Dimensions

Pitch of Ribs, in	Height of Ribs, in					
1/8	0·050	0·040	0·030	0·020	0·015	0·010
1/4	0·050	0·040	0·030	0·020	0·015	0·010
1/2	0·050	0·040	0·030	0·020	—	—
1	0·050	—	—	—	—	—

received the most thorough examination and it is these results that will be discussed here. Rib dimensions tested are shown in Table 1. The ribs were of constant width, 0·025 in and, starting with all ribs 0·050 in high, the smaller sizes were produced by machining down. In choosing these dimensions the authors had the benefit of unpublished work done at Manchester University.

The transformed friction factor and Stanton number are functions of the relative rib height (ε/d_e) and relative rib pitch (P/d_e) in addition to the Reynolds number, and various methods of graphical presentation are possible. In Fig. 4 the friction factor is plotted against the ratio rib pitch/rib height for a constant Reynolds number and for various values of relative height and relative pitch. (A similar plot can be produced for the Stanton number.) It is obvious that, for a fixed height of rib, when the rib pitch becomes so small that the ribs touch each other the surface must

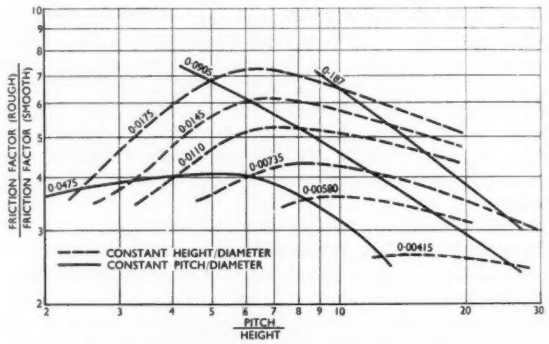


Fig. 4.—Friction factors for isolated rib rough surfaces at a Reynolds No. of 2×10^5.

behave as smooth, and it must approach smooth surface behaviour again as the pitch becomes very large. At some intermediate value of the pitch the friction factor must attain a maximum and this is seen to occur when the pitch is six to 10 times the height, depending on the height. The lowest solid line in Fig. 4 for a constant relative pitch indicates that for pitch/height ratios below about six the rib height has little or no influence on the friction factor. This is brought out very clearly by the form of presentation used in Fig. 5. This figure not only demonstrates that a particular friction factor can be produced by many combinations of rib pitch and height but also shows that two very different regimes exist, the friction factor being nearly independent of rib height at pitch/height values below about six.

The improvement in Stanton number can be compared with the increase in friction factor by means of Fig. 6. It should be pointed out that the width of the band in which the experimental points lie is not a reflection of experimental scatter; indeed each point is based on a considerable number of tests on a particular roughened surface. The existence of the band is an indication that Nunner[2] was incorrect in suggesting that a particular value of Stanton number always corresponds to the same value of friction factor irrespective of the form of the surface that produced them. Apart from a boundary to this group of experimental points the lower line in Fig. 6 has little significance

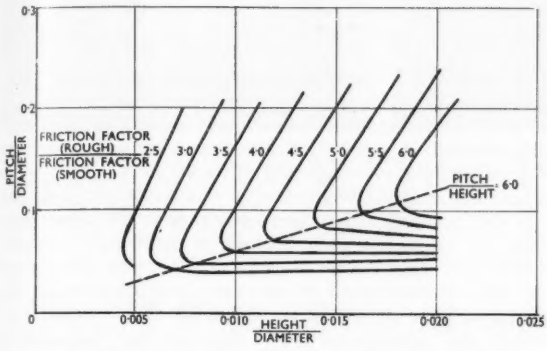


Fig. 5.—Relationship between pitch and height of roughness for constant values of friction factor. Reynolds No. 2×10^5.

in that it would be possible, although rather pointless, to devise surfaces—very large ribs at large pitches—to give poorer ratios of Stanton number to friction factor. The upper curve is of more importance because it may be very difficult to find roughened surfaces of the rib type to give points above this line although there is evidence that other types of roughness such as screw threads would do so. The indication from Fig. 6 that the ratio of Stanton number to friction factor deteriorates progressively as both increase, is in keeping with all our experience of roughened surfaces. The figures shown in Table 2 for the normalized friction factor/Stanton number ratio are based on the upper curve of Fig. 6.

TABLE 2. Normalized Results

$\frac{St}{St_s}$	$\frac{f/f_s}{St/St_s}$
1·0	1·0
1·5	1·125
2·0	1·265
2·5	1·43
3·0	1·77

Although all the results discussed have referred to ribs of rectangular shape, further experiments with ribs that had been chamfered in various degrees or substantially rounded off have shown that, for a fixed height, rib shape has a quite negligible effect, a finding that confers a valuable degree of freedom on the choice of manufacturing process for roughened cans.

APPLICATION TO FUEL ELEMENTS

It is obviously impossible to discuss here the complete reoptimization of a reactor design consequent upon the introduction of roughened surfaces. Assuming that roughened surfaces will not be used to affect the thermal performance appreciably we shall consider a single reactor channel whose performance is kept constant. Referring to Ginn's equation:—

$$\frac{\theta_{sm}-\theta_1}{\theta_2-\theta_1} = \tfrac{1}{2} + (\tfrac{1}{4}\operatorname{cosec}^2(\pi L/2L') + (\beta A)^2/St.S_H.L)^{-1}$$

the left-hand side is to be maintained constant, L, L' and β are fixed, and so is the channel coolant flow rate since the heat removal rate is fixed. It follows that $A/St.S_H$ must also be unchanged. Neglecting the acceleration terms in the Guggenheim pressure drop formula:—

Δp is proportional to $f/A^2 d_e$, i.e., fS_H/A^3

assuming that the channel surface area is negligible compared with the fuel element surface area.

If the channel diameter and therefore A is fixed then $S_H \propto 1/St$; i.e., if roughening doubles the Stanton number the fuel element surface area can be halved. The pressure drop changes in proportion to f/St and will therefore increase if, as is usual, roughening increases the friction factor more than the Stanton number.

On the other hand if A is allowed to vary and the surface area S_H is kept constant then:

$$A \propto St$$

and $$\Delta p \propto f/St^3$$

Thus the pressure loss does not increase if, for a doubling of the Stanton number, roughening does not produce more than an eight-fold increase in friction factor.

The practical case lies between these two simple examples but closer to the first one. The principal aim is to reduce

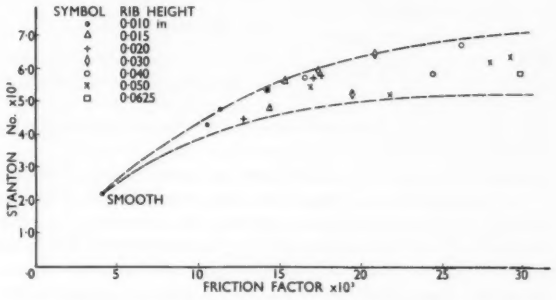


Fig. 6.—Stanton No. v. friction factor for isolated rib rough surfaces. Reynolds No. 2×10^5.

the fuel surface area S_H, at the same time taking advantage of the rapid variation of pressure loss with flow area to avoid an increase in pressure loss.

The preceding discussion involves a number of simplifications. For example it takes no account of parasitic loss caused by fuel element supports. For the same amount of fuel in the channel:

$$\text{Number of rods in cluster } n \propto S_H^2$$

$$\text{and rod diameter } d \propto 1/S_H$$

Consideration of thermal bowing of fuel rods indicates that larger diameter rods can tolerate a greater unsupported length. A channel of roughened fuel elements would therefore contain fewer supports and show a reduction in parasitic pressure loss. This effect, although not large in view of the low pressure loss factors associated with current support grids, has been allowed for in the calculations discussed below.

Detailed Rod Cluster Calculations

The following parameters have been held constant throughout the calculations relating to a CO_2 cooled channel:—

Mean coolant pressure ($\bar{p}$)	285 psia
Coolant pressure loss (Δp)	4.8 psi
Coolant inlet temperature (θ_1)	250°C
Coolant outlet temperature (θ_2)	540°C
Maximum surface temperature (θ_{sm})	650°C
Fuel length (L)	12 ft
Coolant mass flow rate (W)	5·18 lb/s
Channel heat output (Q)	760 kW
Ratio of maximum to average flux (β)	1·4

It has also been assumed that a fuel element support grid is needed every 25 rod diameters and that the pressure loss

TABLE 3. Fuel Element Calculations

	Smooth Rods	Roughened Rods
Fuel perimeter (S_H), in	49·2	27·2
Fuel rod diameter (d), in	0·274	0·511
Number of rods in cluster (n)	57	17
*Number of rods in channel (N)	1 197	204
Number of support grids	22	13
Fraction of pressure loss caused by support grids	0·24	0·097
Channel flow area, in^2	9·13	10·88
Channel diameter, in	4·0	4·26

* It is assumed here that the fuel rod length is equal to the support grid spacing although in practice there might well be advantages in continuing rods through several support grids.

at each grid is 0·075 velocity heads. The friction factors and Stanton numbers were determined according to:—

$$\left.\begin{aligned} f &= 0.050\ Re^{-0\cdot2} \\ St &= 0.0285\ Re^{-0\cdot2} \end{aligned}\right\} \quad \text{for the smooth rods}$$

and

$$\left.\begin{aligned} f &= 0.0150\ Re^{-0\cdot005} \\ St &= 0.0048\ Re^{+0\cdot0085} \end{aligned}\right\} \quad \text{for the roughened rods}$$

The location of this particular roughness is shown by an asterisk on Fig. 6.

The results of the calculations are contained in Table 3.

In one important respect the above comparison is biased against the roughened rods, in that for pressure loss calculations it has been assumed that the channel is roughened similarly to the rods. This has been done for two reasons. It greatly simplified the calculations and, more important, it has been thought wise to introduce this safety factor in view of the uncertainty felt in applying the Windscale roughened surface data to rod clusters because of the marked differences in both shape and proportions of smooth and roughened surfaces between a rod cluster and the apparatus from which the data were determined. This uncertainty has always been greater on pressure loss rather than on heat transfer because, in applying Hall's method described above to separate out the influence of the smooth, unheated channel, the adjustment to the friction factor was large, a factor of up to two, whereas the Stanton number was much less affected. However, recent measurements showed that to treat the channel as roughened also has been unnecessarily pessimistic, overestimating the pressure loss by perhaps 20%, and that a more refined calculation making further use of Hall's method to allow for the presence of a smooth channel and a roughened cluster, agrees to better than 10% with pressure loss measurements made on 21 rod clusters with two different types of roughness.

One of the most difficult heat transfer problems associated with rod clusters is to distribute the rods correctly in the channel so that all positions in the cluster attain the specified maximum temperature. A substantial margin must be allowed between the nominal maximum temperature (θ_{sm}) and the absolute maximum permitted value to allow for the spread of temperatures in the reactor, one contribution to which arises from any failure to achieve the ideal distribution of rods in the cluster. It should be much easier to achieve the correct distribution when handling 17 rods rather than 57 and the roughened cluster might therefore have been allowed an increase in θ_{sm} on the strength of a reduced spread of temperatures. However, any such improvement is probably not very striking and at present the advantages of roughened surfaces show up in ways other than a direct improvement in thermal performance.

If both smooth and roughened cans have the same thickness the roughened ones contain an appreciably smaller quantity of steel; on the other hand if for strength reasons the can thickness had to increase in proportion to the diameter there would be no reduction in the amount of steel. The assumption of a constant can thickness is probably more correct. Metallurgical considerations such as a corrosion allowance and the ratio of the size of inclusions to the can wall thickness point towards a constant wall thickness; so far as can strength is concerned it is found that the roughening ribs increase the resistance to deformation under gas pressure differences out of all proportion to the material added by the ribs. In fact the ribs in the example given above are 0·0054 in square at 0·054 in pitch and represent only 3% of the steel in the channel (assuming a 0·015 in thick can). This is of course the reason for choosing this form of roughness for steel cans although on purely heat transfer grounds a continuous roughness such as a screw thread would be rather more efficient, giving a better ratio of Stanton number to friction factor. The smaller number of support grids in the roughened cluster leads to a further reduction in the amount of steel but the amount of steel in the grids is not large. It will be obvious that the channel of roughened fuel elements, because it contains so many fewer individual rods, should be appreciably cheaper to manufacture.

Finally mention should be made of the limitations set by centre fuel temperatures in UO_2 fuel elements. Previous experience with uranium-magnox fuel elements is being repeated in that the heat rating and rod diameter were initially limited by the rate of heat removed from the can surface, but improvements in convective heat transfer, in this case associated with the use of roughened surfaces, have made possible increases in diameter and/or rating such that the limitation may well be set by the maximum central fuel temperature that can be tolerated from considerations of fission product diffusion.

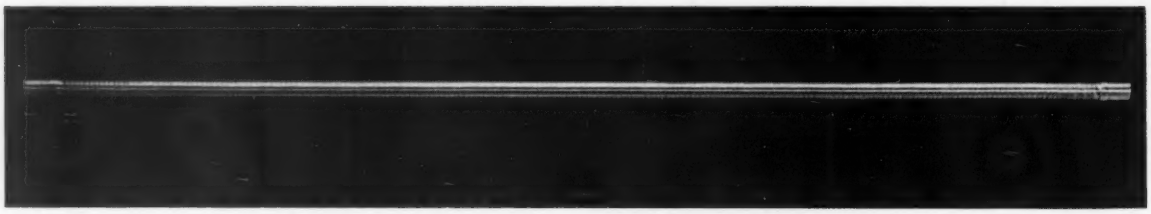


Fig. 7.—A closer view of the roughened surface fuel can shown in Fig. 3.

Acknowledgments

The authors wish to acknowledge the help of Mr. P. Burnett and Mrs. M. Bertram who with the assistance of Mrs. P. Sinclair, were responsible for the collection of the experimental data on rough surfaces. They are also indebted to the managing director, U.K.A.E.A, Development and Engineering Group, for permission to publish this article.

REFERENCES

1. Hall, W. B. "Heat Transfer in Channels Composed of Rough and Smooth Surfaces." I.G.R.–TN/W.832 (1958).
2. Nunner, W. "Heat Transfer and Pressure Drop in Rough Tubes." AERE Lib./Trans. 786. Translated from V.D.I. Forshungshaft 455, Supplement to "Forshung auf dem Gebiete des Ingenisurwesens." B, Vol. 22, pp. 5–39 (1956).

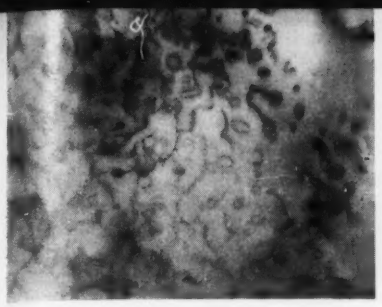


Fig. 1.—Transmission electron micrograph of a thin film of beryllium after irradiation with $\sim 10^{22}$ fast neutron/cm² while at ~100°C, showing dislocation loops.

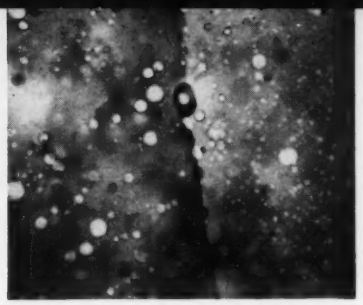


Fig. 2.—A thin film of beryllium after irradiation with $\sim 10^{21}$ fast neutron/cm² and subsequently heated at 900°C for 1 h, showing the appearance of the helium bubbles.

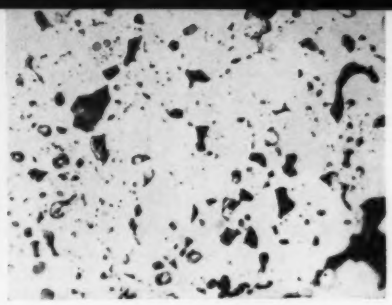


Fig. 3.—The mechanically polished surface of the same beryllium as that shown in Fig. 2 but after heating at 1 000°C for 1 h, showing large holes lying mainly on the grain boundaries.

The Effect of Neutron Irradiation on Beryllium

by **R. S. BARNES** (*Metallurgy Div., AERE, Harwell*)

THE low thermal neutron capture cross-section (0·01 barn) and high melting point (1 290°C) make beryllium a feasible material for use in the core of a thermal power reactor either as a canning or structural material, and its low atomic weight makes it ideal as a moderator or reflector material. However, in assessing the capabilities of beryllium its attractive nuclear properties must be balanced against its less desirable properties, e.g., its breakaway corrosion, its toxicity and its low ductility which limit both the fabrication methods and the component designs which may be used.

In assessing the effect of irradiation upon the material not only must the normal displacement of atoms, which occurs in all materials, be considered but also the results of nuclear transmutation during fast neutron bombardment in which helium is the main product. The displaced atoms recover their normal positions at temperatures in excess of approximately one half the absolute melting temperature, ($T_m/2$=500°C in beryllium) so that above this temperature the material is little changed. However, the effects of the impurities introduced during the transmutation are permanent.

The following are the two fast neutron reactions (with thresholds of 3 MeV and 2 MeV respectively) which occur in beryllium, which consists solely of the isotope ${}_4Be^9$:

$${}_4Be^9 + {}_0n^1 \rightarrow 2\,{}_2He^4 + 2\,{}_0n^1 \text{ (cross-section 0·53 barn)}$$

$${}_4Be^9 + {}_0n^1 \xrightarrow{\beta} {}_2He^4 + {}_3Li^6 \text{ (cross-section 0·8 barn)}$$

The amount of helium produced in one year may be as much as 0·1 at.% or about 1 cm³ of gaseous helium at NTP per cm³ of the beryllium. If the beryllium is used for the fuel can, the fast neutron flux is at a maximum, but the nuclear and physical deterioration of the fuel necessitate replacement of the entire fuel element at regular intervals so that the build up of the helium is limited. For a fuel element configuration such as that to be used in the Windscale AGR the fast neutron flux to the can expressed in n/cm² will be approximately 10^{17} times the burn-up to the fuel in MWd/t; i.e., 10 000 MWd/t will see the cans receiving a fast neutron dose of about 10^{21} n/cm². As a moderator or structural material, beryllium would generally suffer a lower fast flux but as it should preferably remain in the reactor throughout its life the helium content might exceed 20 cm³/cm³. Experiments with highly irradiated beryllium are beginning to reveal some of the effects of irradiation and these will be outlined.

Effect of Point Defects

Each time a fast neutron makes a direct collision with the nucleus of a beryllium atom, which only happens once every few cm of travel, up to about one third of the neutron's energy is transferred and the beryllium atom then dissipates this kinetic energy by violently interacting with the other atoms lying in its path. These are knocked out into the crystal and the energy of the slower moving ones is focused into crystallographic directions and eventually an atom comes to rest in the position between the normal atomic positions, becoming an interstitial atom. There may be around 1 000 produced at each such primary collision. Vacancies, in equal numbers, are left behind in the positions of the originally displaced atoms. The interstitial atoms can normally migrate at reactor operating temperatures and either they can recombine with vacancies, with mutual annihilation, or they can cluster together to form extra plates of atoms lying on certain crystallographic planes. Such clusters can be seen in beryllium irradiated with $\sim 10^{22}$ fast neutron/cm² which has been subsequently electrolytically thinned until it is only about 10^{-5} cm thick (see Fig. 1). These films are transparent to the electrons used in an electron microscope but at the edge of the plate of extra plane there is a discontinuity and a distortion of the lattice which diffracts the electrons differently, such that the edge (which is equivalent to a dislocation loop) can be seen as a dark loop in Fig 1. The belief that these loops are due to clusters of interstitial atoms and not vacancies, stems from analogy with the behaviour of similar loops observed in irradiated copper. The vacancies are believed to be so dispersed that any clusters which exist are smaller than the resolving power of the electron microscope which is $\sim 10^{-7}$ cm.

The movement of the dislocations, which exist in all metals, enables deformation to occur, and is impeded by these inhomogeneities and dislocation loops in the crystal. The hardening effect is similar to that caused by precipitates. Such hardening is observed after quite short doses, e.g., $\sim 10^{18}$ fast neutron/cm², in pure metals.

Effect of Helium Atoms

In normal metals, these clusters of vacancies and interstitial atoms disappear by a process of self-annihilation on heating an irradiated material to a temperature at which self-diffusion can occur ($\sim T_m/2$), but when there are an appreciable number of helium atoms within the material (and about one atom in every 100 is a helium atom in beryllium after $\sim 10^{22}$ fast neutron/cm²) the behaviour is modified. This helium is unable to diffuse out of the beryllium except near the melting point. Above the self-diffusion temperature the helium atoms (which probably quickly move to clusters of vacancies forming embryo gas bubbles) capture any further vacancies which are generated, each

vacancy providing the space of one atom and allowing a reduction in the gas pressure. The vacancies are provided at dislocation lines (for instance at the plates of interstitial atoms which increase in size and do not shrink on heating) and at grain boundaries. Such gas bubbles can be seen in beryllium which has been irradiated with $\sim 10^{21}$ fast neutron/cm^2 and then heated to 900°C for one hour. An electron micrograph of a thin film is shown in Fig. 2 where the bubbles appear as light patches, because the electrons are more readily transmitted through them. Some of the larger white patches should be disregarded, as here the bubbles have been enlarged during the thinning process to such an extent that "pin-holes" have formed in the foil. No bubbles are seen in Fig. 1, either because the bubbles are too small or have not formed, although there is more helium.

The motion of dislocation lines is impeded by these bubbles which lie like a string of beads along them and harden the beryllium. The hardening is a function of the number of bubbles per unit volume as the stress needed to bow a dislocation between neighbouring bubbles, such that it breaks away from them, is inversely proportional to the distance between the bubbles. The ability of the beryllium to deform by twinning is also restricted, and it becomes less ductile.

The pressure P of the helium in a bubble, is normally balanced by the surface energy γ, so that $P=2\gamma/r$ where r is the radius of the bubble. For instance, some of the bubbles shown in Fig. 2 have a radius of 10^{-5} cm so that the helium they contain is at about 200 atm, when it can occupy little volume.

At higher temperatures more vacancies become available so that the volume occupied by the gas increases and the pressure further reduces and of course the beryllium swells. The number of gas bubbles must reduce if the pressure balance ($P=2\gamma/r$) is to be maintained and observations such as that illustrated by Fig. 2 show that this does happen. The spacing between the bubbles thus increases and the hardening effect diminishes as the material swells. Eventually at very high temperatures the bubbles become very large with a further reduction in the gas pressure (although the pressure can never fall below the ambient pressure in the reactor). Large holes appear in the grain boundaries, as shown in Fig. 3, which is a normal optical micrograph of the same beryllium as that shown in Fig. 2 but after heating to 1 000°C for one hour, when it had increased in volume by 30%, largely due to these holes which lie in the grain boundary.

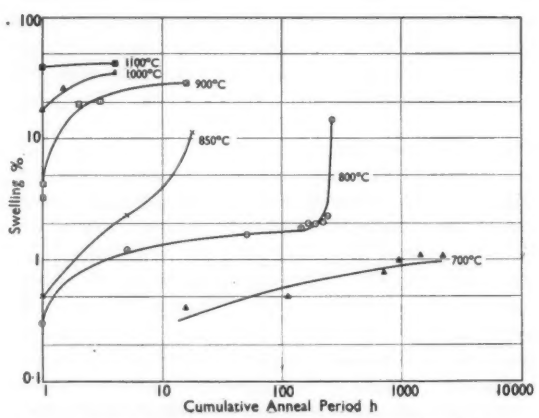


Fig. 4.—The percentage volume increase produced by a beryllium specimen after heating for various times and at various temperatures.

Changes in Properties

Experiments in the Harwell reactors have demonstrated that after irradiation at 350°C the effect upon the mechanical properties is not marked up to doses of about 10^{20} fast neutron/cm^2. This is to be expected as the helium atomic concentration from such a dose ($\sim 10^{-4}$) is still well below the impurity level normally present. It seems probable that the impurity content reduces the effect of the vacancies and interstitial atoms, as in pure metals such a dose would produce a marked change. Above this does the mechanical properties change appreciably, the beryllium becoming harder and more brittle. This effect is diminished if the irradiation is performed at higher temperature (for example, irradiation at 600°C up to doses of 3×10^{20} fast neutron/cm^2 produces little change), or even if it is heated after irradiation. However, the temperature necessary for this is greater than 800°C after doses of $\sim 10^{21}$ fast neutron/cm^2, which suggests that the hardening at these high doses is caused predominantly by the helium and not by the displaced atoms.

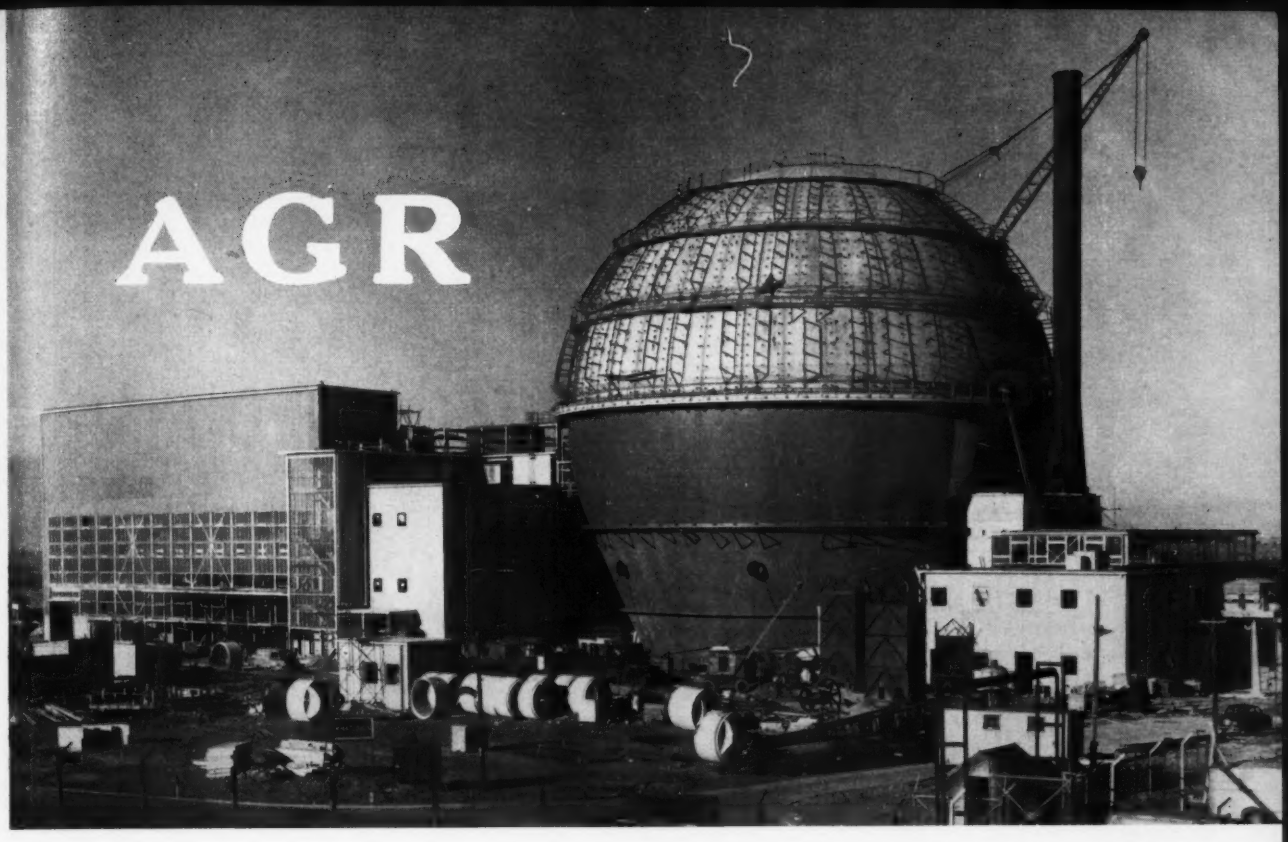
After higher doses and as the temperature of irradiation (or a subsequent heat treatment) rises, the bubbles which form are larger, and so the swelling increases. This effect is illustrated in Fig. 4 which shows the percentage volume increase resulting from various heat treatments of beryllium which has been bombarded with $\sim 10^{21}$ fast neutron/cm^2. At temperatures below 700°C this beryllium does not swell by more than about 1% because the bubbles are so small. The bubbles seen in Fig. 2 have produced $\sim 3.5\%$ increase in volume.

Moving grain boundaries can sweep up helium which is dispersed either atomically or in small bubbles and collect it into larger bubbles which, provided the temperature is high enough, can be dragged along by the boundary. In this way larger bubbles can form on the boundary than would normally occur at the temperature concerned. If excessive swelling is to be avoided it is necessary to prevent grain boundary movement. The bubbles themselves impede the migration of the boundaries, but if the driving force is sufficient, the bubbles will merely be swept along. In beryllium formed from powder (the usual fabrication method) the impurity particles on the grain boundaries (i.e. the interfaces between the original powder particles) prevent their movement and make this sweeping process unlikely.

The effect of the helium upon the corrosion of beryllium is not marked and even at high temperatures when appreciable swelling has occurred the only effect appears to be due to an increase in the surface area resulting from bubbles which have broken the surface.

Summary

The effect of irradiation upon the properties of beryllium does not become apparent until doses in excess of 10^{20} fast neutron/cm^2. Thereafter the main effect is to reduce the ductility if the irradiation temperatures are low (less than about 500°C), and at these temperatures the volume change is negligible. At temperatures above 700°C the volume increases (up to a maximum $\sim 30\%$ at high temperatures) and there is less effect upon the ductility. Where ductility is essential, the fast neutron dose must be limited and this limit will be less severe at higher operating temperatures. A limit to the temperature will be set by the advent of swelling. For components which are regularly replaced, only the limitation of the temperature may be important. Where ductility is of little consequence, e.g. in a moderator material, much higher doses can be tolerated but then, if swelling is to be avoided, the temperature will have to be restricted to much lower values than would be acceptable in fuel element cans.



Ace Film Productions

THE Advanced Gas-cooled Reactor, forerunner of the "second generation" of power stations, was first publicly described at the 1958 Geneva Conference* and a brief description and schematic drawing were published in *Nuclear Engineering* for October, 1958, p. 431. Construction commenced at a site near the old Windscale piles, in October, 1958, and is sufficiently near completion to warrant a more detailed description.

The Windscale AGR is primarily an experimental reactor; a fuel element test bed designed to give maximum flexibility to the experimental programme. With its associated physics research reactor Hero (*Nuclear Engineering*, April, 1960, p. 150) and exponential stacks, it is to provide the essential data for the second generation of British stations. Graphite moderated and CO_2 cooled, the AGR system was conceived as burning oxide fuel in beryllium cans. A great deal of effort has been put into the development of beryllium, in the belief that the better neutron economy would more than offset the disadvantages of high cost of raw material and fabrication, toxicity, and possible lower burn-up than might be achieved with stainless steel. Development of beryllium has been slower than was hoped, but fabrication problems are now largely resolved, its irradiation stability appears adequate (see p. 149) and—provided its corrosion resistance can be made sufficiently high—its practicability as a canning material should be demonstrated. Until the middle of last year it was hoped that a major proportion of the first fuel charge would be beryllium-canned but it has now been decided that only experimental channel loops are to be so fuelled.

General Description

The arrangement of AGR can be appreciated from the pull-out drawing facing page 152, from which it will be seen that the entire reactor and its associated boilers or heat exchangers are enclosed within a steel containment building, isolated from the fuel handling building and the turbine house. The reactor pressure vessel, which occupies a central position within the containment, is surrounded by four heat exchangers connected to the pressure vessel by radial coolant ducts, and surrounded by individual biological shields.

Communication with the turbine building, which also houses the administrative offices, etc., is via a large air lock. There are two communication routes between the containment and the fuel element building. New fuel is passed into the reactor charge/discharge machine via a "clean" way through air locks; irradiated fuel leaves the charge/discharge machine via vertical chutes to a carousel, or revolving magazine, located beneath ground level and provided with a closed-circuit CO_2 cooling system.

The general philosophy adopted in the construction of the reactor pressure vessel has been to separate, so far as possible, the effects of pressure and temperature, i.e., to ensure that components which are called on to resist high pressure, should not simultaneously be exposed to high temperatures. This involves double-shell construction, the gas flow being so arranged that the outer shell, carrying the full system pressure, is swept by the cooler gases, while the "hot" enclosures are only required to withstand differential pressures of a few psi. The application of this principle to duct construction using concentric ducts with the hot gas in the inner duct, has also assisted in the solution of thermal expansion problems, by allowing freedom from multi-point restriction.

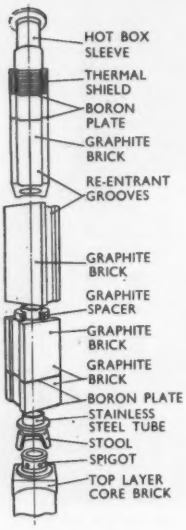
Core and Coolant Flow

The core is designed on a 10¾ in triangular lattice, with 253 channels. The graphite stack approximates to a cylinder of active diameter 15 ft (18 ft 4 in over reflector) and 14 ft high (18 ft over reflector). It is principally constructed of rectangular bricks 10·75 in × 9·3 in in section and 31 in long, drilled centrally to form 5¼ in dia. fuel channels and grooved on all four faces to form passages for the flow of part of the inlet coolant gas. The section of the grooves tapers towards the bottom to improve the temperature distribution in the core by increasing the gas velocity (and hence heat transfer) as the cooling gas temperature rises. Individual layers of blocks are keyed together by scalloped ferrules with chamfered bores of minimum diameter 5·1 in which locate the fuel element stringers. Adjacent rows of blocks are offset (see Fig. 1) to form the triangular pitch. The whole core is supported on ball bearings on a diagrid resting on columns welded to the bottom dome and is restrained by a system of beams and garter "springs," at each course.

* "Advances in the Design of Gas-cooled Graphite Moderated Reactors." Paper No. 312, by R. V. Moore, H. Kronberger and L. Grainger.

Continuity of fuel channels is maintained by stainless steel tubes connected via stool and spigot joints to the top of each core channel, and this runs upwards through the neutron shield and hot-box to appropriate nozzles in the vessel dome.

The space between the hot box and neutron shield is crossed by a pin-jointed tube, this method of support accommodating



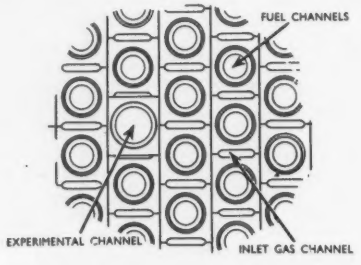


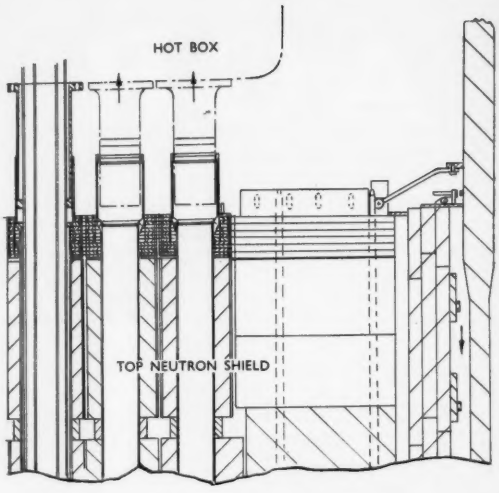
Fig. 1 (Above).—Section through the neutron shield showing the lattice arrangement. In the core all block faces are grooved to form cooling channels.

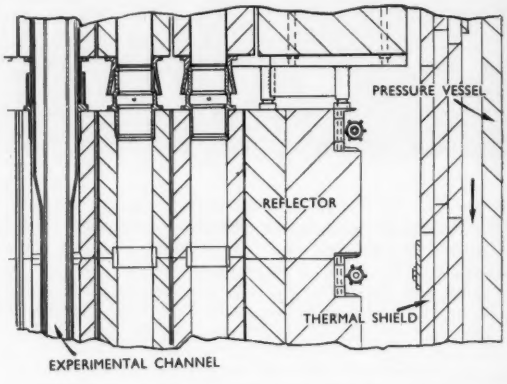
Fig. 2 (Left).—Exploded view of channel through the neutron shield.

differential radial movement between hot box and shield. The pitch of the channels in the two sections is different in the cold state so that the junction tubes are almost vertical at operating temperatures. The hot box itself is a calandria type unit with stub tubes attached. Above it the channels are carried through by tubes provided with sliding joints, which penetrate the baffle plate and connect with the nozzles in the reactor vessel. Ports are machined in the tubes running through the hot box to line up with sleeve valves in the fuel element stringers. The setting of these valves is adjustable from the charge floor with the reactor on load by means of a key, the rotary movement being converted in the stringer to a linear motion and the valves being operated by push rods. Sealing between fuel element stringer and channel tube is by means of piston rings.

Certain channels, designated as experimental loops, have a stainless steel tube running the whole length from top to bottom domes; these run "blind" through the hot box and are connected to external cooling circuits. Flow is re-entrant passing

Fig. 3.—Core support plates on the triangulated diagrid.





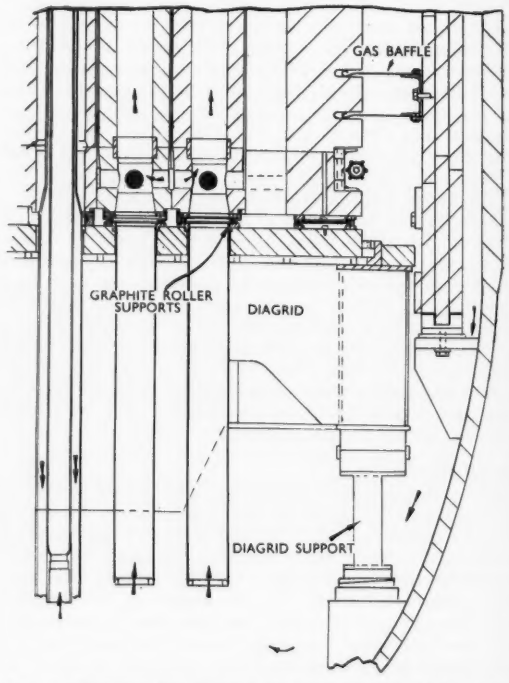


Fig. 4.—Part sections of core and top neutron shield (the experimental channel has been displaced).

The World's Reactors

No. 32 Windscale AGR

OWNER: U.K.AEA.

PURPOSE: Experimental; power production.

LOCATION: Windscale, Cumberland.

DESIGNER: U.K.AEA.

TYPE: Thermal, heterogeneous, CO_2 cooled graphite moderated.

PROGRAMME:
Site work commenced: October 1958.
Critical: summer 1961.
Power operation: end of 1961.

CAPACITY:
Thermal output: 100 MW.
Gross electrical output: 33 MW.
Net electrical output: 27·3 MW.

FUEL:
Enriched uranium oxide pellets.
Density: $\geq$ 95% theoretical.
Average fuel rating: 8·6 MW/t(U).
Maximum fuel rating: 19·5 MW/t(U).
Total charge: 13·2t.

CLADDING: Stainless steel, 0·015 in wall, or beryllium, 0·040 in wall.

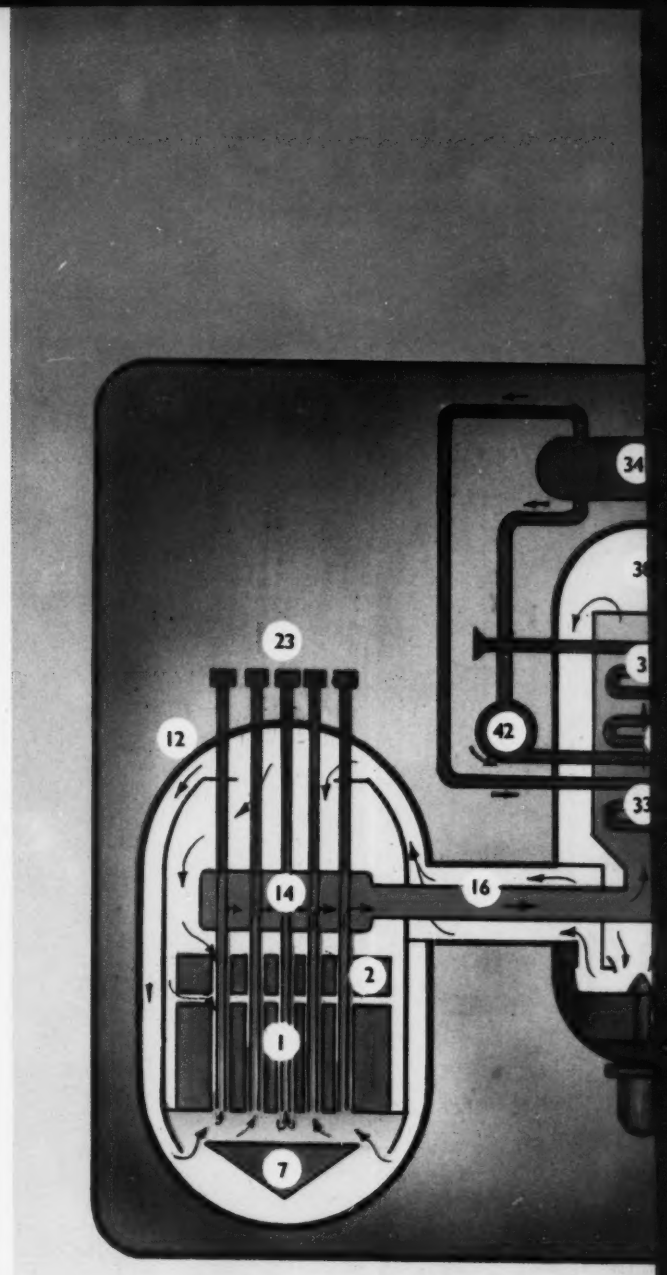
FUEL ELEMENTS:
Stainless steel clad:
4 fuel element assemblies in graphite sleeve, 5 in o.d. on central tie rod, per channel.
Sub-assemblies: 2 clusters × 21 fuel elements.
Elements: 0·43 in o.d. × 18 in long.
Pellets: 0·400 in dia. × 0·400 in long.
Enrichment: 2.5% U^{235}.
Maximum can surface temp.: 650°C.
Expected burn-up: 10 000 MWd/t.
Beryllium clad:
4 fuel element assemblies in graphite sleeve, 5 in o.d. on central tie rod, per channel.
Sub-assemblies: 3 clusters × 36 fuel elements.
Elements: 0·38 in o.d. × 12 in long.
Pellets: 0·300 in dia. × 0·300 in long.
Enrichment: 1.8% U^{235}.
T_{sm}: 600°C.
Expected burn-up: 10 000 MWd/t.

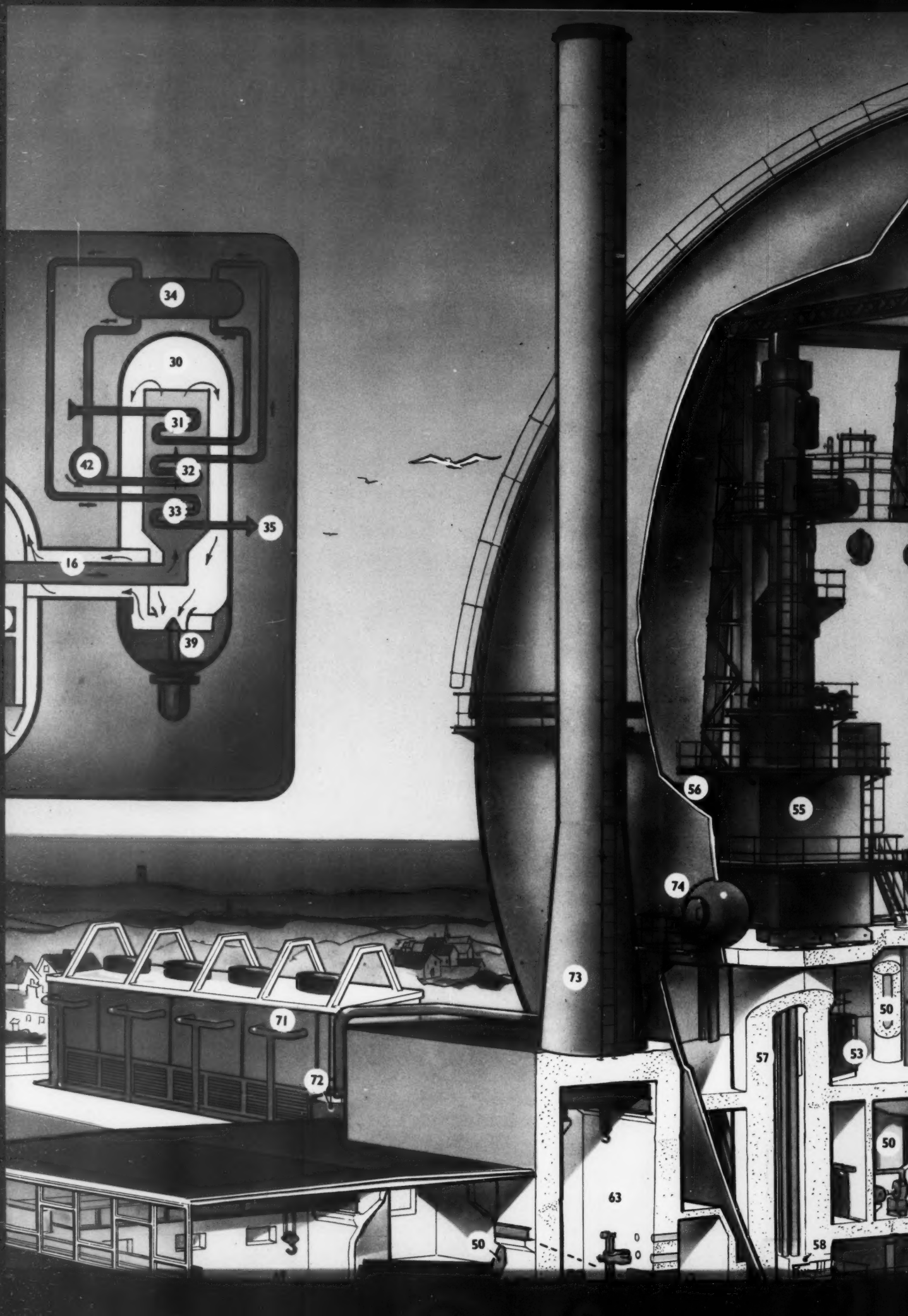
CORE:
Moderator and reflector: graphite.
Dimensions: 15 ft dia. (nom.) × 14 ft high.
Reflector: 20 in radial; 24 in axial.
Graphite weight: 210 ton.
No. of bricks: 3 000.
Lattice: triangular, 10¾ in pitch.
No. of main channels: 253.
Core contains five independently cooled loops.
Initial charge in main core: stainless steel clad.
Experimental channels: beryllium clad elements.
Core is unflattened.

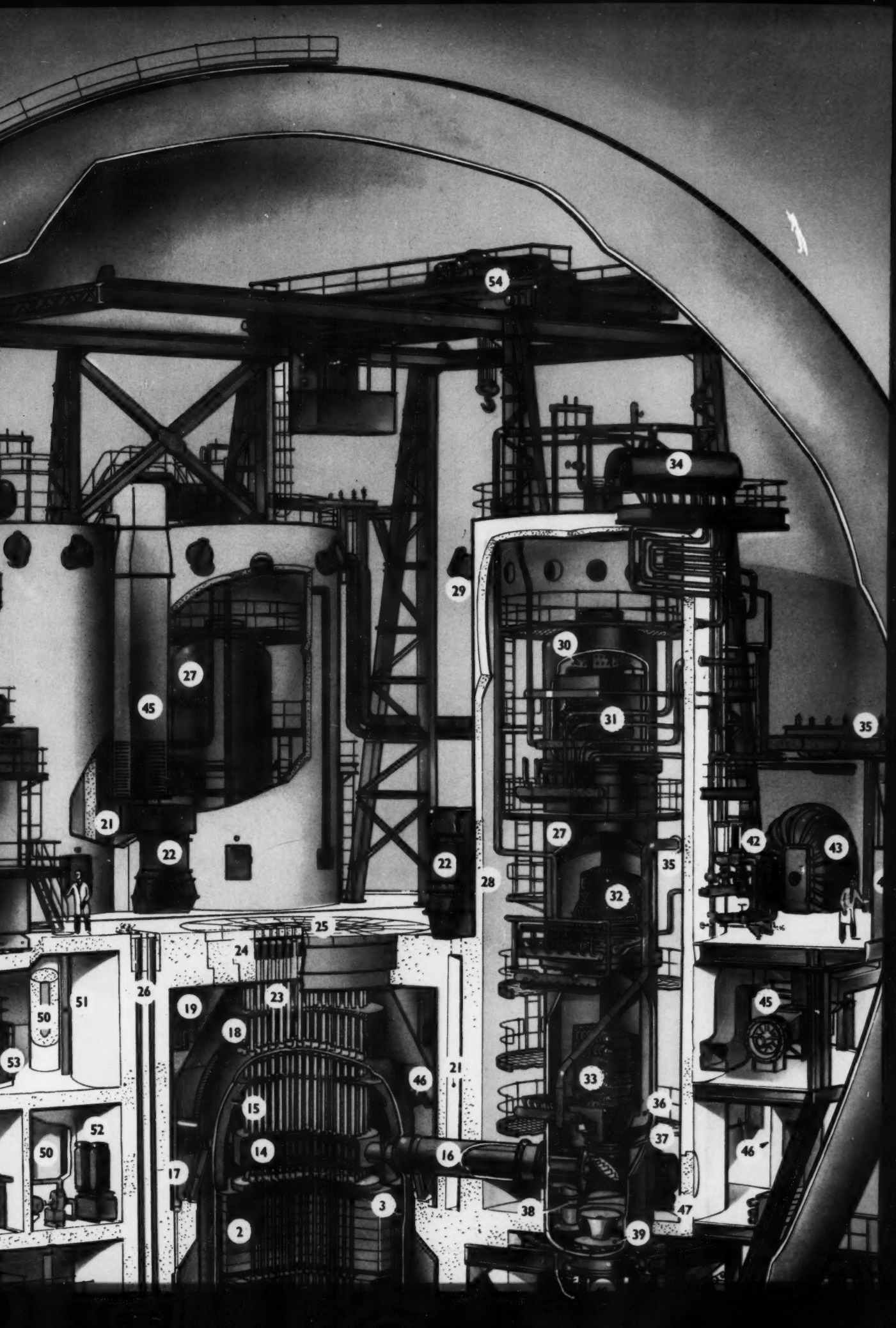
PRESSURE VESSEL:
Cylindrical with hemispherical ends.
Overall height 53 ft 6 in, 21 ft 3 in o.d.
Thickness, barrel portion: plain strakes: 2⅞ in.
Support strakes: 4⅜ in and 3¼ in.
Ends: 1¾ in-3⅞ in.
Total weight: 250 ton approx.
Material: Al-killed, grain-controlled mild steel, type Conlo 1.
Closure: all welded.

COOLANT:
CO_2.
Working pressure: 270 psig.
Inlet temperature: 250°C to 325°C.
Outlet temperature: 500°C to 575°C.
Total gas in system: approx. 14 ton.
Rate of circulation: 760 lb/s (approx. 20 ton/min).
Flow is re-entrant through core, final pass upwards.

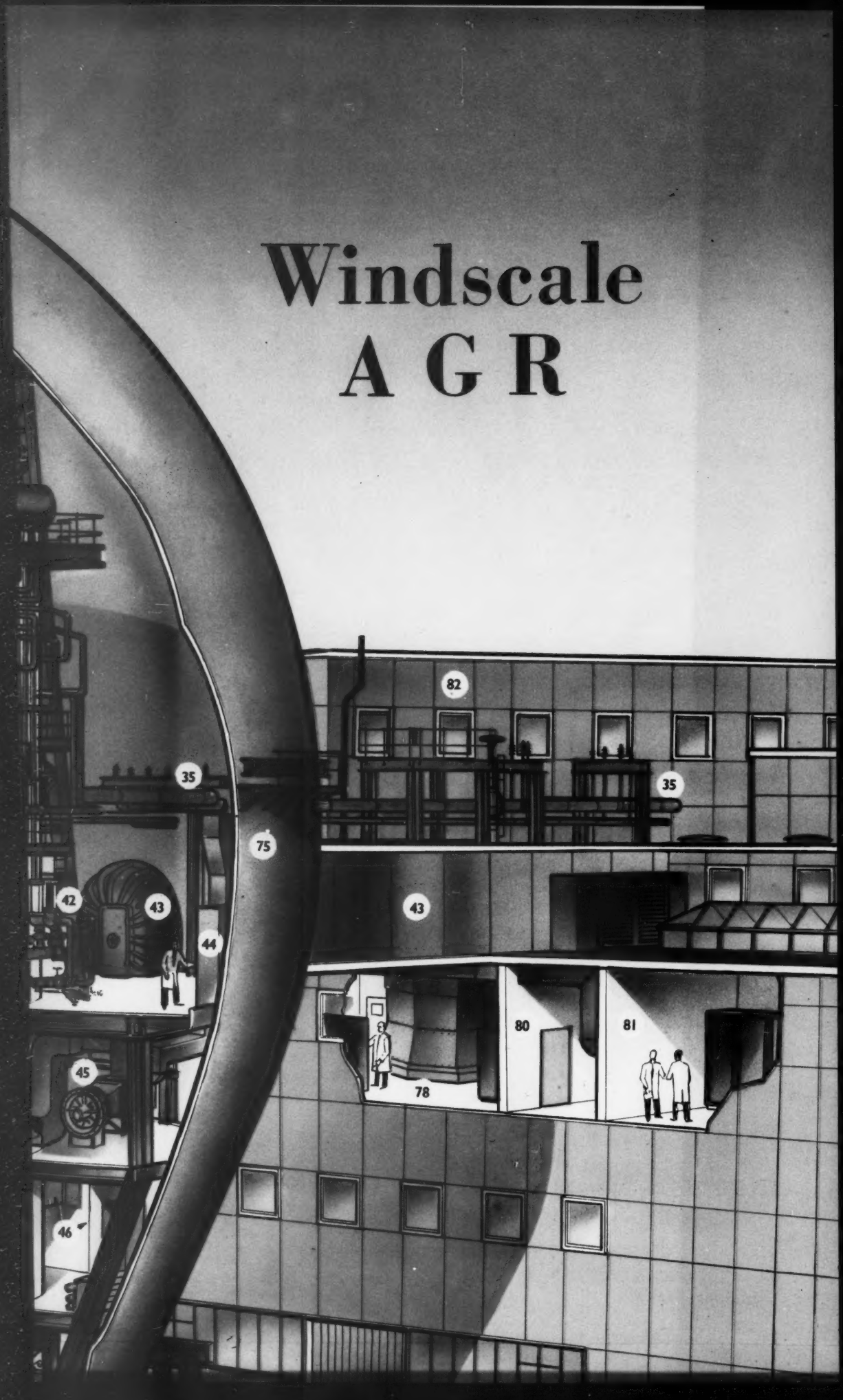
HEAT EXCHANGERS:
Four: 11 ft dia × 67 ft 9 in overall height.
Wall thickness: 1 7/16 in.
support strake: 2½ in.
Heat exchange surface for evaporator and economizer section: 2 in o.d. ERW tube with extended surface of ½ in helical fins, pitched 6 in.
Superheater section: plain unfinned 2¼% Cr/1% Mo tube.
Heat transfer area for each exchanger:
Economizer 11 750 ft².




34
30
31
42
32
33
35
16
39
56
55
74
73
71
72
50
57
53
50
63
50
58


54
34
29
30
31
35
27
45
21
22
22
28
27
42
43
35
32
25
24
26
23
19
18
51
50
53
45
21
46
33
36
15
52
50
14
16
37
46
17
3
38
47
2
39

Windscale AGR



HEAT EXCHANGERS:	Four: 11 ft dia × 67 ft 9 in overall height. Wall thickness: $1^{7}/_{16}$ in. support strake: $2\frac{1}{2}$ in. Heat exchange surface for evaporator an 2 in o.d. ERW tube with extended surf pitched 6 in. Superheater section: plain unfinned $2\frac{1}{4}$% C Heat transfer area for each exchanger: Economizer 11 750 ft². Evaporator 30 800 ft². Superheater 4 240 ft². Concentric gas ducts between reactor 1 ft 11 in and 2 ft 10 in diameter, carbon Forced circulation evaporation. Steam conditions 650 psi, 850°F (454°C).
CIRCULATORS:	Four, centrifugal type. Capacity of each: 190 lb/s. Pressure differential 28 psi. Fixed speed: 3 000 rev/min. Flow control: by adjustable inlet vanes. Drive: 1 570 h.p. squirrel-cage a.c. motor,
CONTROL:	Coarse control: 12 manually operated boro Reactivity controlled: approx. 7-8%. Fine control: 3 manual/auto stainless steel Reactivity controlled: $\frac{1}{4}$% each. Auto responds to exit gas temperature. Emergency shut-down: 1·4% boron stainle Reactivity controlled: approx. 3%. No. of channels involved: 8 provisionally.
SHIELDING:	Top and side, thermal: 6 in steel. Top neutron: 7 ft graphite interleaved with plates. Biological side: 7 ft 6 in concrete. Biological top: 6 ft concrete. H.E. side: 2 ft concrete.
CONTAINMENT:	Steel building with hemispherical upper portion and flat bottom. Max. dia.: 135 ft. Base dia.: 76 ft 8 in. Height above ground level: 134 ft. Plate thickness: $1^{15}/_{16}$ in max., $\frac{1}{2}$ in min. Total weight (excluding air locks): 850 ton Area: 58 500 ft². Capable of withstanding 10 psi internal pres exceeding 0.1% of net volume in 24 h.
TURBINE:	33 MW, 3 000 rev/min, 2-cylinder impulse 850°F, 28.6 inHg vacuum.

Printed in England by Temple Press Limited, Bowling Green Lane, London, E.C.1.

all height.

vaporator and economizer section:
xtended surface of ½ in helical fins,

inned 2¼% Cr/1% Mo tube.
changer:

en reactor and heat exchangers:
eter, carbon steel.
F (454°C).

et vanes.
a.c. motor, with pony motor.

perated boron steel rods.
7-8%.
ainless steel rods.
perature.
oron stainless iron balls.
3%.
ovisionally.

el.
erleaved with seven ⅛ in boron steel

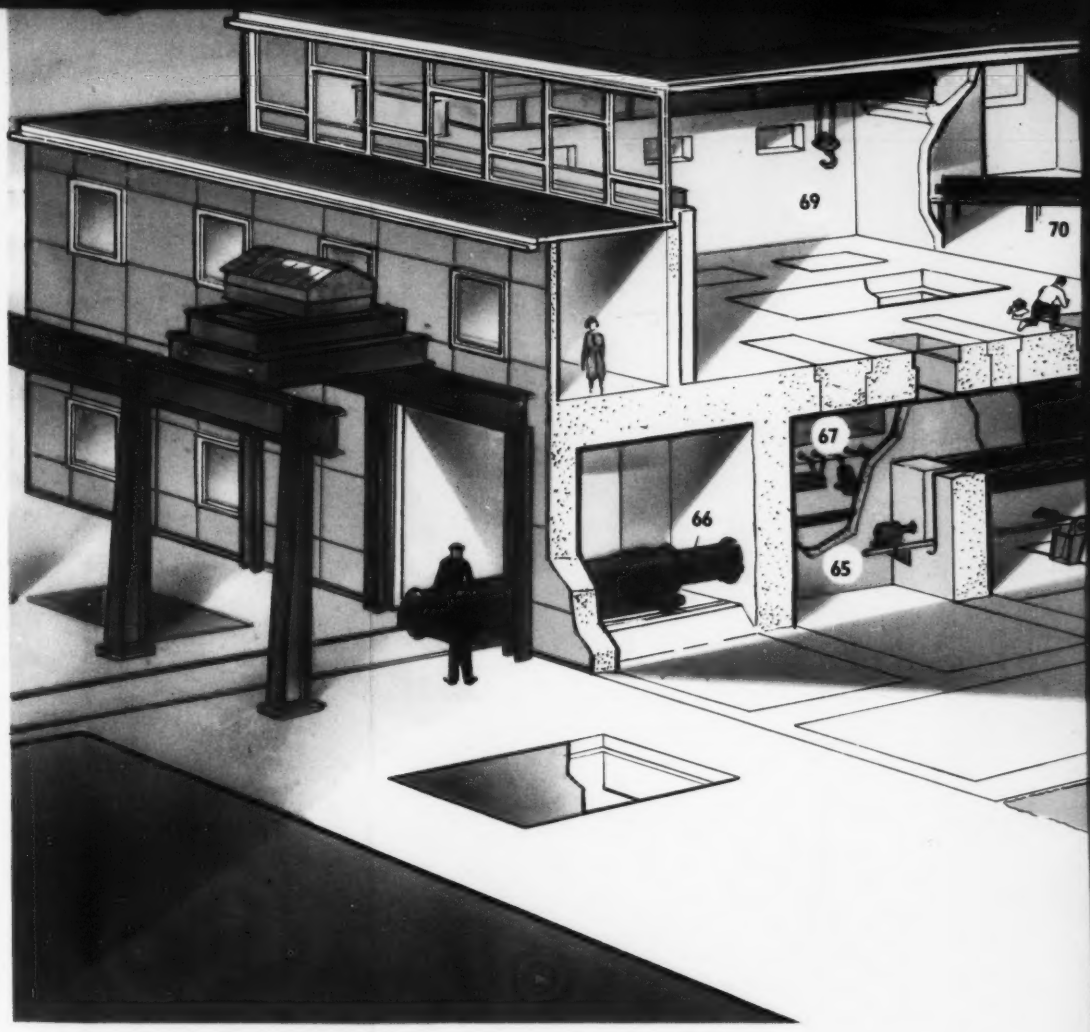
ete.

rical upper portion, conical lower

4 ft.
½ in min.
ks): 850 ton.

internal pressure with leak rate not
me in 24 h.

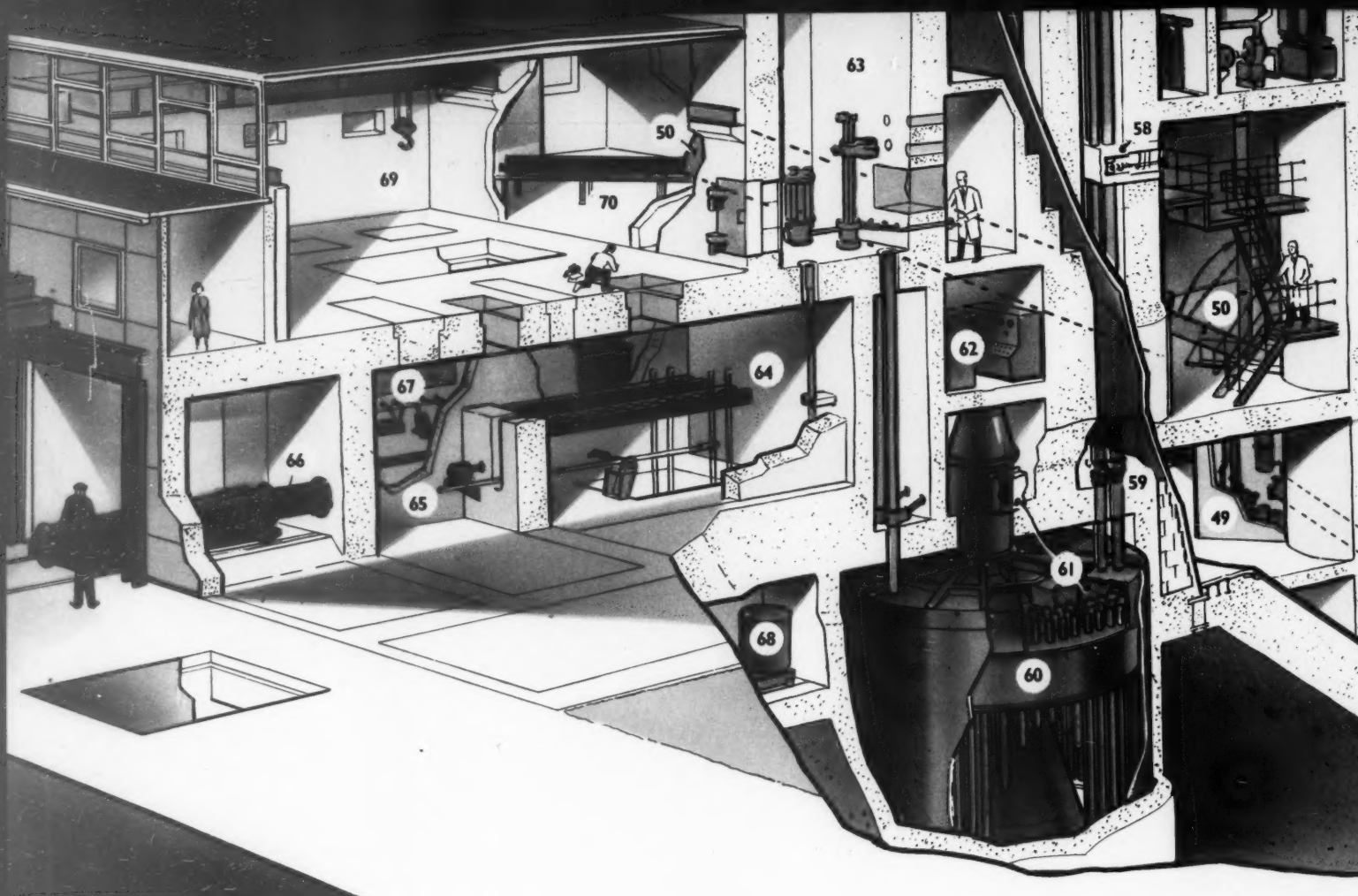
der impulse-reaction type 650 psi.



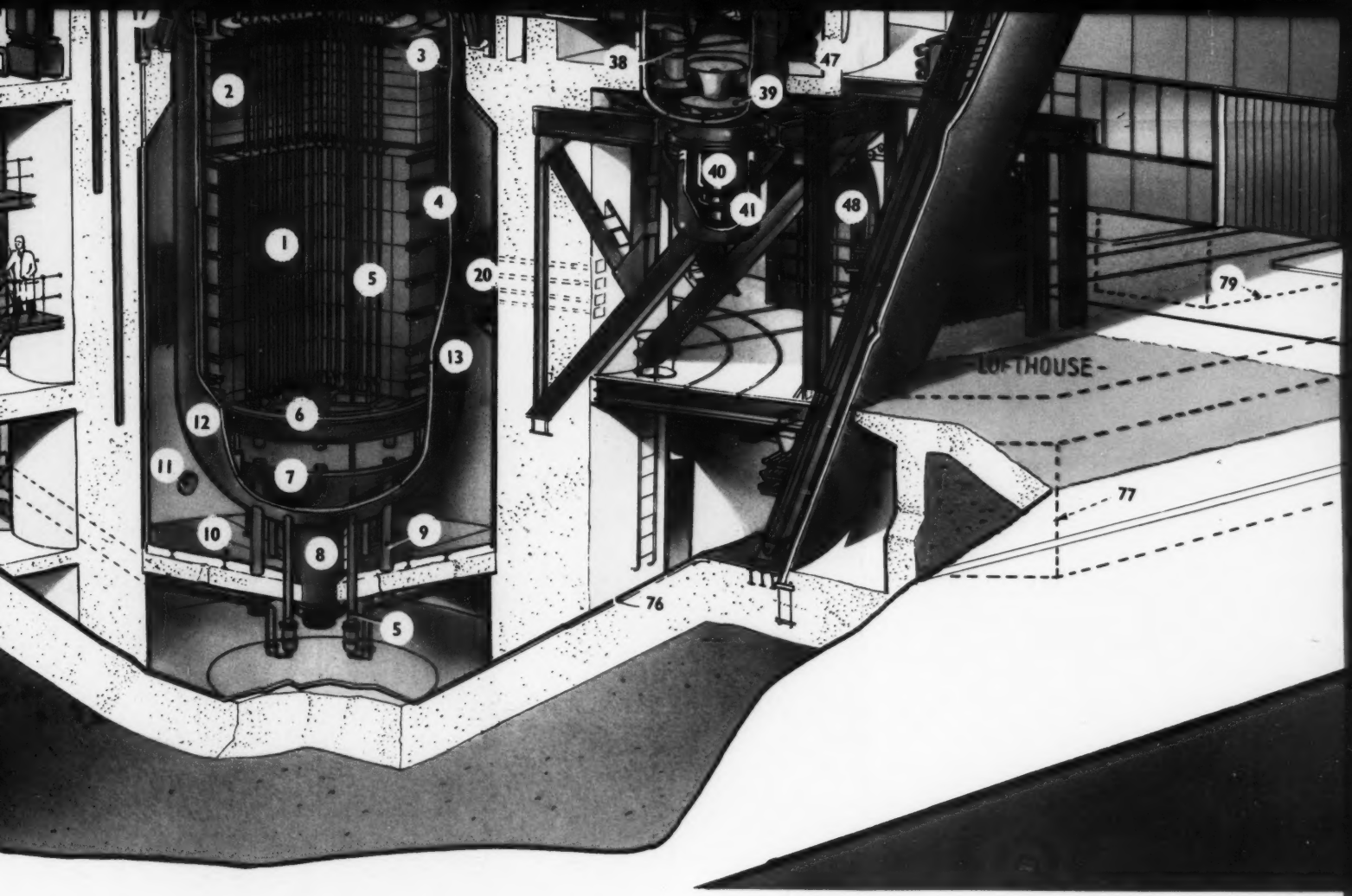
AGR KEY

1. Core
2. Top neutron shield
3. Thermal shield
4. Core restraint
5. Experimental channels
6. Diagrid
7. Tundish
8. Bottom dome access
9. Viewing branches
10. Bottom cooling membrane
11. 4 ft gas main
12. Pressure vessel
13. Inlet gas seal
14. Hot box
15. Gas baffles
16. Concentric ducts
17. Pressure vessel support members
18. Top dome lagging
19. Shield cooling ducts
20. Thermal columns
21. Inter-shield coolin
22. Inter-shield coolin
23. Channel stand-pip
24. Control rod moto
25. Removable top shi
26. Control rod storag
27. Heat exchangers
28. Heat exchanger bi
29. Shield pressure rel
30. By-pass duct diffuse

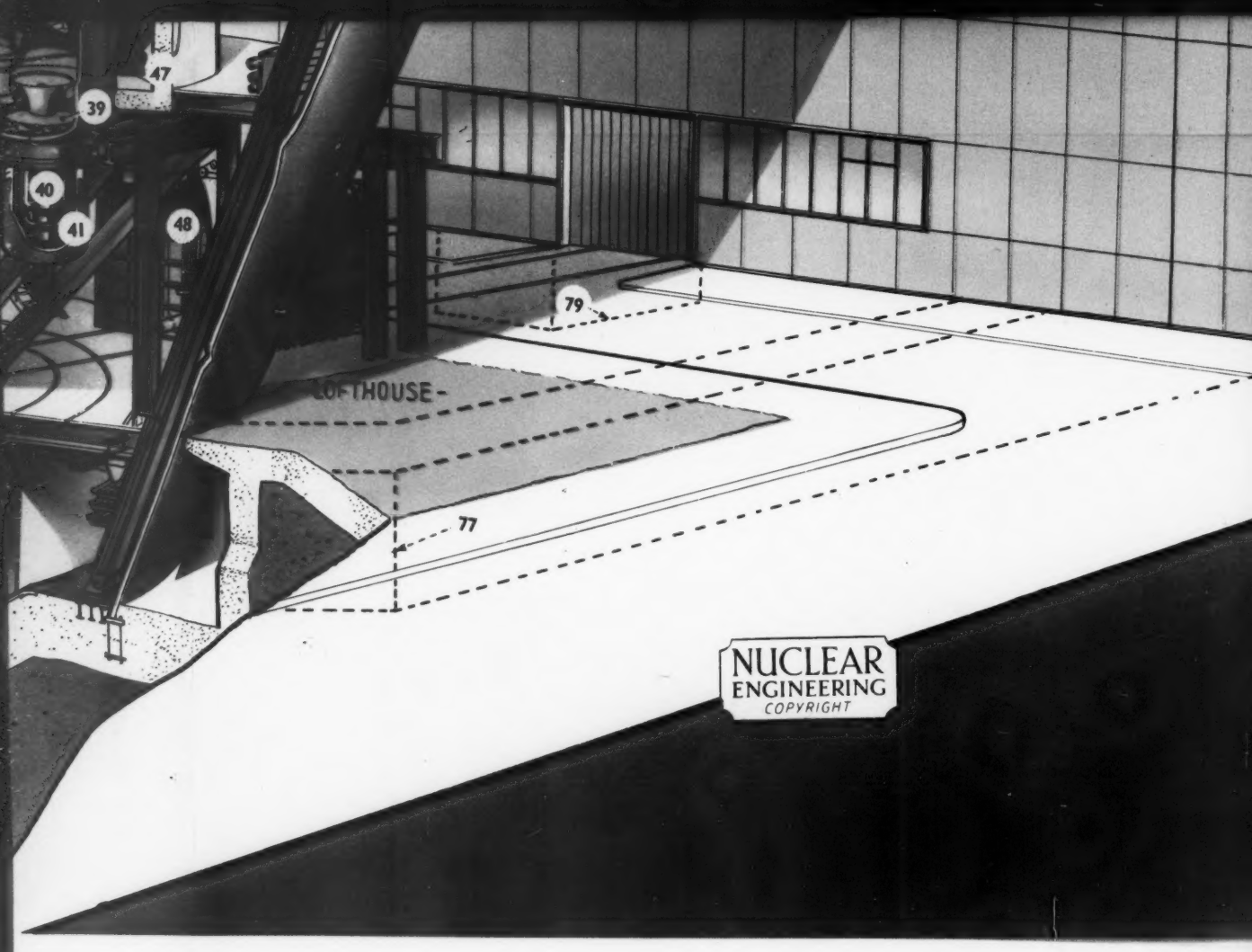
London. E.C.1.



11. 4 ft gas main
12. Pressure vessel
13. Inlet gas seal
14. Hot box
15. Gas baffles
16. Concentric ducts
17. Pressure vessel support members
18. Top dome lagging
19. Shield cooling ducts
20. Thermal columns
21. Inter-shield cooling ducts
22. Inter-shield cooling fans
23. Channel stand-pipes
24. Control rod motors
25. Removable top shield
26. Control rod storage
27. Heat exchangers
28. Heat exchanger biological shield
29. Shield pressure relief valves
30. By-pass duct diffusers
31. Economizer
32. Evaporator
33. Superheater
34. Steam drum
35. Steam pipe to T.S.V.
36. By-pass ducts
37. Hot valve
38. Cold valve
39. Circulator
40. Circulator drive motor
41. Circul
42. Circul
43. Perso
44. Local
45. Conta plant
46. BFED
47. H.E. r
48. Goodr
49. Test c
50. New



41. Circulator pony motor
42. Circulating pumps
43. Personnel lock and walkway
44. Local H.E. panel
45. Containment vessel ventilation plant
46. BFED equipment
47. H.E. rolling supports
48. Goods air lock
49. Test cells
50. New fuel facility
51. Hot pressurized test facility
52. Spent element plant room
53. Graphite sampling room
54. Reactor service crane
55. Charge/discharge machine
56. Pressurizing / depressurizing C/D m/c room
57. Spent fuel chute
58. Uncoupling facility
59. Transit tube air locks
60. Spent fuel carousel
61. Carousel cooling system
62. Carousel control room
63. Stringer break-down cave
64. Shield plugs and control rod store
65. Inspection cave
66. Transit flask for s.p.s and c.r.s
67. Dismantling cave
68. Spent fuel element transit
69. Gantry hall
70. New fuel element assembly room
71. Cooling towers
72. Ventilation chemi
73. Stack
74. Emergency air loc
75. Containment shell
76. Sealing membrane
77. Cable ducts
78. Reactor control ro
79. Emergency reactor
80. Ventilation plant r



61. Carousel cooling system
62. Carousel control room
63. Stringer break-down cave
64. Shield plugs and control rod store
65. Inspection cave
66. Transit flask for s.p.s and c.r.s
67. Dismantling cave
68. Spent fuel element transit
69. Gantry hall
70. New fuel element assembly room
71. Cooling towers
72. Ventilation chemical plant
73. Stack
74. Emergency air lock
75. Containment shell
76. Sealing membrane
77. Cable ducts
78. Reactor control room
79. Emergency reactor control room
80. Ventilation plant room
81. Electrical control room
82. Turbine hall

© TEMPLE PRESS LIMITED. 1961.

D. 1961.

upwards over the fuel elements and down through a concentric annulus to the experimental rooms in the basement of the building. Provision for six experimental channels has been made of which four will now contain loops, the remaining two forming part of the normal core but containing special elements.

In order to limit the effect of a positive moderator temperature coefficient at high burn-up the inlet coolant gas is caused to sweep through the stack and maintain its near the inlet gas temperature. The equilibrium temperature of the stack should correspond closely to that for minimum Wigner growth.

Cool gas entering the reactor vessel by the four outer ducts divides into three separate flows, approximately as follows:—

About 46% is deflected by a gas deflector inside the vessel, and after sweeping the upper surface of the vessel and round the

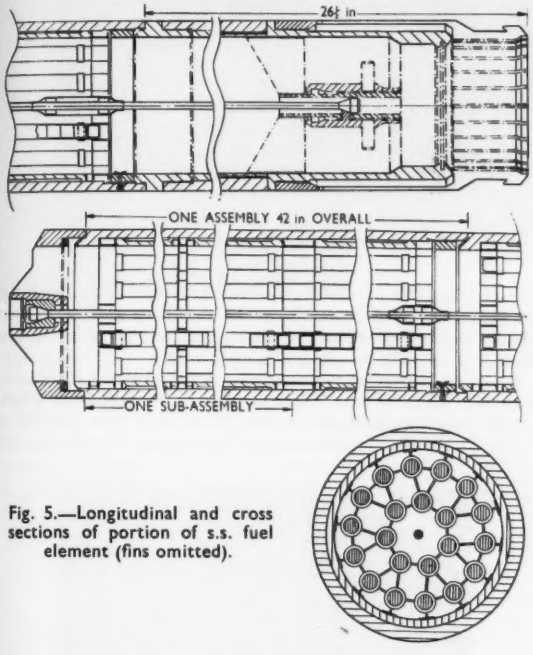


Fig. 5.—Longitudinal and cross sections of portion of s.s. fuel element (fins omitted).

hot box, which is internally lagged, it flows downward through the grooves in the graphite to the bottom of the core. About the same amount is deflected outside the radial thermal shield, down and over the tundish joining the first flow at mixing spaces in the bottom reflector bricks. (See Fig. 4.)

The remainder, rather less than 10% of the total, enters the space between the top of the core and the neutron shield, flows down outside the graphite sleeves of the fuel elements and rejoins the rest to flow up through the elements to the hot box and from thence through the four inner ducts and bellows units to the column of the heat exchangers.

Immediately over the core is a neutron shield made up of 7 ft of graphite interspersed with seven ⅛ in sheets of boron steel which leads to a more compact overall design by reducing the amount of biological shielding necessary outside the vessel. It also prevents neutron streaming along the coolant ducts, thus enabling the use of the short concentric ducts without introducing right-angled bends. Radial shielding consists of a total thickness of 6 in steel plate surrounding the core. Below the core, axial shielding takes the form of a 3 in thick mild steel tundish which, in addition to acting as a thermal shield, also serves to collect any debris from the reactor which might break away during operation and direct it to a central branch from which it could be removed after shut-down.

Fuel Elements

A complete fuel element stringer comprises four assemblies in series contained in a double graphite sleeve 5 in o.d. and held together by a stainless steel tie rod. The assemblies are made up of two (in the case of stainless steel) or three (Be)

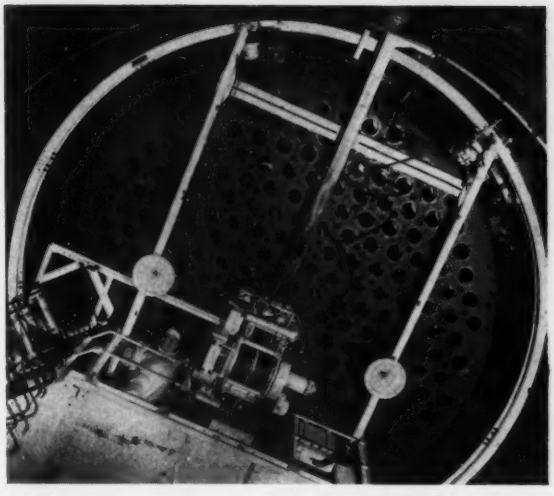


Fig. 6.—Temporary crane inside pressure vessel engaged in laying core support plates. (Hot box has been slung above crane level.)

sub-assemblies each comprising a bundle of 21 (s.s.) or 36 (Be) elements. The individual elements contain UO_2 pellets, whose lengths equal their diameter, in an atmosphere of helium. Automatic machines have been developed for helium arc welding the end caps on a complete push button basis.

Considerable effort has been put into the development of "roughened" surfaces to improve heat transfer (see p. 144) and the first core of stainless steel canned elements will be made up with cans carrying circumferential fins 0·007 in high × 0·007 in wide on a 0·09 in pitch.

The fuel element assembly proper ends at the top in a sprung

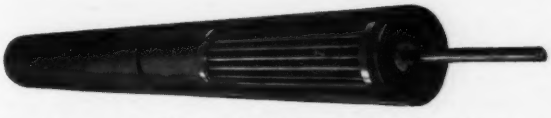


Fig. 7.—General view of Be element assembly with portions of graphite sleeves cut away.

collet over which is fitted the supporting steel extension piece and shield plug. A sliding joint of limited movement takes up thermal expansion and distributes the load (around 1 000 lb) of a complete stringer when installed in the core between the arrester mechanism carried on the diagrid and the top latch mechanism to which the refuelling machine can be attached, in the proportions of roughly two to one.

Control

Control of the reactor is by means of rods operated from above the reactor and the design of the drives forms a separate article. In addition an emergency system of shut-down is provided which involves the release of 0·25 in dia. boronated stainless iron balls into the core volume. These are stored in the centre section of a 50 ft long tube divided into three flexibly jointed sections and are retained by an electromagnetic valve designed to operate in a temperature of 400°C. The upper section contains the shield plug and the lower two sets of concentric graphite tubes forming an annulus into which the balls can fall. A remotely controlled sleeve valve at the bottom allows them to be discharged when the mechanism has been removed from the reactor.

Pressure Vessel

A great deal has recently been written about the design of pressure vessels, and brief reference to a feature of this actual vessel is to be found elsewhere in this issue† where the

† "Pressure Vessels for Gas-cooled Graphite-moderated Reactors." I.Mech.E. paper by Noone and Bishop, p. 170, this issue.

reinforcement of the top dome is discussed; the stress intensification around the refuelling nozzles is compensated by a general thickening of the top dome, giving the effect of double reinforcement of the plate, and allowing the use of nozzles of

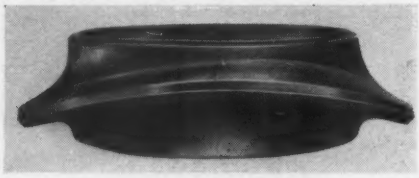


Fig. 8.—Forged cambered duct ring for pressure vessel.
(Courtesy English Steel Corporation)

much lighter construction. This considerably reduces the risk of cracking and assists working to finer tolerances.

The vessel is approximately 21 ft i.d. and 53 ft 6 in overall length. The barrel was constructed in five strakes, of which the lower four are $2\frac{7}{8}$ in thick. The top strake, which takes the supports and the four gas ducts, is $3\frac{1}{4}$ in thick, except in the vicinity of the gas ducts, where it is $4\frac{1}{8}$ in. The top dome, which has 253 branches on a $10\frac{3}{8}$ in triangular lattice, is $3\frac{7}{8}$ in thick over the reinforced portion and $1\frac{1}{4}$ in thick over the remainder.

The lower dome carries, in addition to a large central branch,

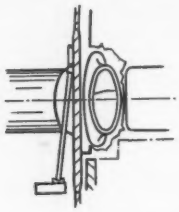


Fig. 9.—Diagram showing method of pressure vessel support, to eliminate vertical movement of duct plane.

six nozzles for experimental channel loops (of which only four will now be used) and six viewing nozzles.

Construction throughout is in silicon-killed aluminium grain-controlled mild steel—Conlo 1 (less accurately referred to in the pull-out as "aluminium-killed"). After erection, stress relieving was carried out at 600°C.

Supporting the vessel itself, however, provides one of the most interesting features of the design. The amount of thermal expansion to be accommodated is considerable and, to enable the gas ducts to be kept simple, both the pressure vessel and the heat exchangers are supported in the same horizontal plane, very near to that of the gas ducts, so that at duct level the

Fig. 10.—Welding nozzles in dome of pressure vessel.

expansion of the whole system is, for all practical purposes, purely radial.

At the pressure vessel, support is provided by 20 rocker-plate units with rounded ends rolling at the upper end in grooved fittings welded to the top barrel strake of the vessel and, at the lower end, rolling in grooved support pads in the concrete foundations. The upper ends are slightly above, and the lower ends slightly below, the centre line of the ducts. As a result

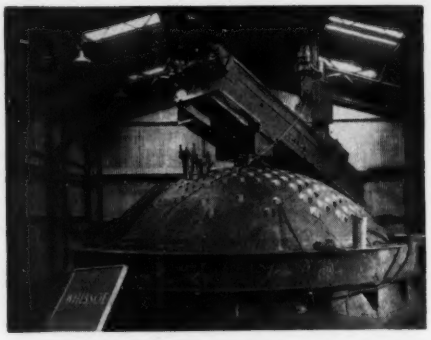


Fig. 11.—Machining nozzle holes in vessel dome.

the small vertical movement due to the change in inclination of the rocker plates is compensated by the downwards expansion of the vessel between the supports and the duct centre, and there is practically no change in duct level.

A further unusual design feature is the support for the diagrid. With the triangular core lattice, it was necessary that the diagrid should be of triangulated construction and it was possible to utilize 12 equally loaded support points inside the vessel; this

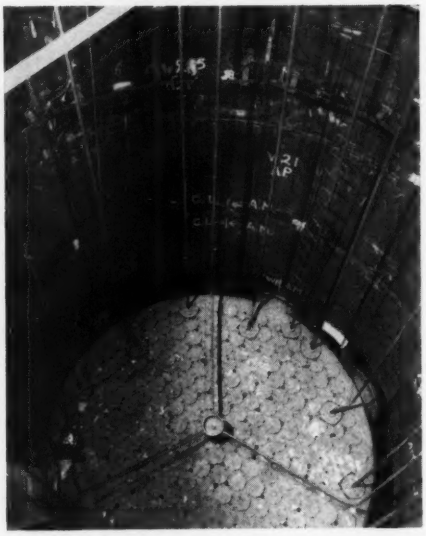
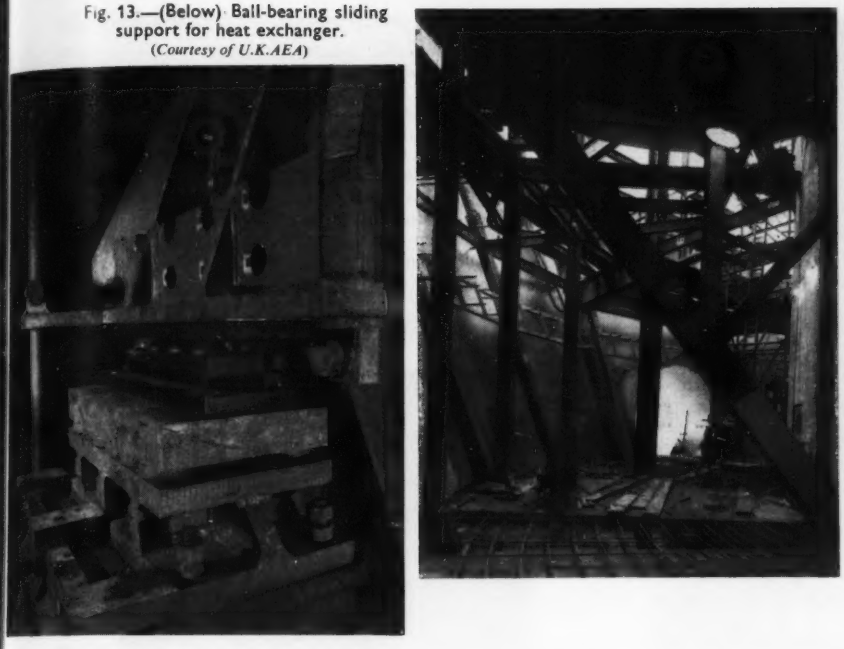


Fig. 12.—Arrangement of heating elements for stress relieving of vessel. (Hot box has been lowered to rest on diagrid.)

equality of loading has not been previously possible with a square grillage. The bottom dome is thickened from $1\frac{1}{4}$ in to $2\frac{1}{4}$ in at the support ring, and distributes the stresses throughout the vessel. This distribution of load made it possible for the vessel to withstand the weight for a hydraulic test.

This vessel is noteworthy in being the first in which rings for the ducting were forged to a curvature suitable for a cylindrical vessel and attached entirely by butt welding; a

Fig. 13.—(Below) Ball-bearing sliding support for heat exchanger.
(*Courtesy of U.K.AEA*)



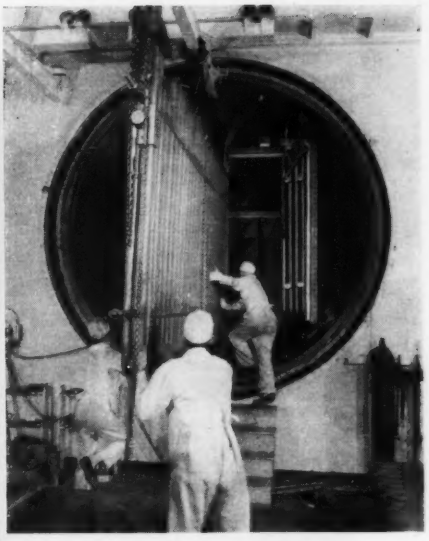


Fig. 14.—(Above) Tube banks being erected in heat exchanger under clean conditions. (Left) General view of supporting steelwork at ground level.
(*Courtesy U.K.AEA*)

considerable step forward in pressure vessel fabrication techniques.

Heat Exchangers

The four main heat exchangers and their manufacture have already been described in these pages by Bennett.** As in the case of the reactor vessel, temperature and pressure effects have been divorced, and the pressure shell is only called upon to withstand the inlet temperature.

Each pressure shell, contained within its own biological shield, is 67 ft 9 in high and 11 ft diameter in low carbon manganese steel $1\frac{7}{16}$ in thick except for the bottom strake on which are mounted the supports carried on six sets of ball bearings; this is $2\frac{1}{2}$ in thick. The inner shell containing the tube banks, is approximately 7 ft square in section and is internally insulated with crimped stainless steel. Unlike previous designs the gas flow is upwards; the hot gas enters at the bottom via an isolating valve from the inner duct, and flows over the superheater, evaporator, and economizer sections, the cooled gas then emerges from the inner shell, sweeps over the pressure shell and passes into the inlet eye of the blower, at the bottom of the shell.

The steam drum is located outside the concrete shielding and the risers and downcomers are arranged with generous expansion loops, to accommodate relative movement between the pressure shell and the drum. Piping is led through the shield via bellows units so that the shield can act as a separate containment volume.

** "AGR Boilers." E. F. P. Bennett (Director, International Combustion (Nuclear Applications), Ltd.). *Nuclear Engineering*, July-August-September, 1959, p. 291.

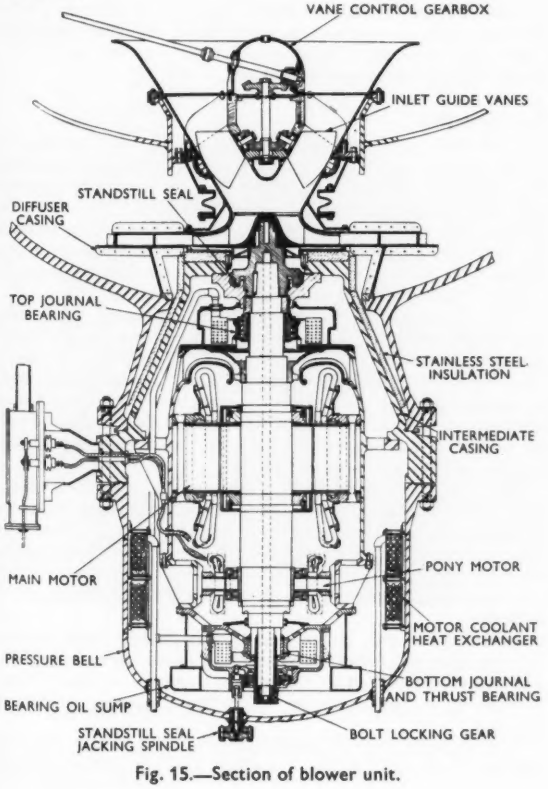


Fig. 15.—Section of blower unit.

Blowers

Canned blowers are used for the gas circulation, located at the bottom of each heat exchanger unit. They are of the single-speed centrifugal type, each driven by a 1 570 h.p. 3 000 rev/min squirrel-cage motor, with a pony motor on the same shaft for emergency operation, power being supplied from a stand-by battery through a motor-alternator set. Normal gas flow is 198 lb/s, with a pressure head of 28 psi, flow control being by variable guide vanes in the inlet bell.

As will be seen from Fig. 15, the impeller (some 3 ft diameter) runs on a stub shaft, which incorporates a gas sealing device on to which it can be lowered at standstill. The main motor shaft is keyed to this stub shaft, and secured by a through bolt so that it can be released from the lower end; the combination of this with the standstill seal enables the complete motor unit to be removed, if required, with the circuit under pressure. Closed-circuit cooling is provided, with a water-cooled heat exchanger for heat removal. The upper portion of the motor is housed under an intermediate casing and crimped stainless steel heat insulation is provided between this and the body of the heat exchanger.

Fig. 16.—Standpipes at charge floor level, before placing finished floor.

Containment

The biological shielding for the reactor is incorporated in the main structure, as will be seen from the pull-out drawing. The central structure also carries the entire load of the heat exchangers and their shields by means of cantilever outriggers cast into the central shield. The load of the building floors is transferred, via a system of heavy brackets, to sloping columns located a few inches inside the skin of the containment building. These columns have rocker bases resting on pads in the foundations. The main foundation is saucer-shaped, 99 ft in diameter and 8 ft thick; its lowest point is 34 ft below ground level.

The containment building has a hemispherical upper portion, its lower portion being an inverted frustrum of a cone. This design was adopted as being more economical of space and material than either a spherical or cylindrical structure. It is 135 ft diameter at the equator, and has a height of 134 ft above ground level. The least diameter of the conical portion is 77 ft at 14 ft below ground level, where it meets the steel membrane forming its floor. It has a weight, excluding airlocks, of 850 tons, and is built from plate varying in thickness from $1\frac{1}{16}$ in to $\frac{1}{2}$ in.

Fig. 17.—Lowering the 3-in thick tundish into place.

It is specified to withstand internal pressures of 10 psi (its surface area is some 58 500 ft²) at which pressure it was stipulated that leakage should not exceed 0.1%/d of the net volume In addition, it had to withstand snow loading of 10 lb/ft² of plan area at a solid angle of 120° from the centre, and a wind velocity of 85 mile/h. Dimensional tolerances for the spherical portion were fixed at 0·25% on the diameter, and 1·375 in on a 14 ft 6 in arc; for the conical portion, the corresponding figure was 1 in on a 5 ft 6 in arc.

Ventilation

Air-conditioning is provided for the working space of the containment building, and an air pressure maintained of some 2 in w.g. above that in the inner containment, i.e., the biological shield system. This differential pressure allows (via controlled leakage through the operating floor and uncontrolled leakage through various construction joints) some 3 000 ft³/min to enter the inner containment cooling system. Here, a controlled flow of some 20 000 ft³/min sweeps the reactor vault and the heat exchanger enclosures via a system of ducts and ring mains. This system might be termed a semi-closed circuit; whilst the majority of the air is recirculated through the cooling plant and

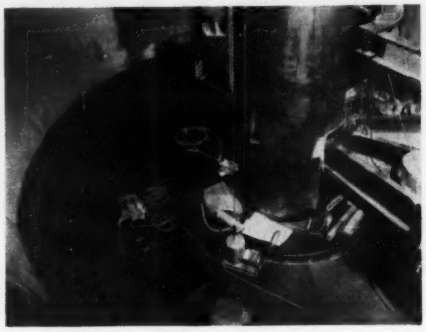


Fig. 18.—Irradiated fuel carousel during construction.

fans, an amount equivalent to the inward leakage from the outer containment (3 000 ft³/min) is filtered, scrubbed, and discharged up the stack.

Other gaseous discharge, such as release of coolant, due to depressurizing or accident, is vented to a chemical absorption plant, with heat sink, filters and activated carbon absorption packs, before discharge to the stack.

Fuel Handling

Fresh fuel is received in the fuel handling building adjacent to the reactor containment building. On the first floor, elements are assembled to form a stringer for the complete channel, and the necessary thermocouples attached. The complete stringer now passes, via a conveyor system, through an inclined air lock into the containment building. It is manually transferred to a vertical chute, where it can be hoisted into the "clean" side of the charge/discharge machine.

The charge/discharge machine is approximately 65 ft high, and weighs 400 tons. It is self-propelled and can be positioned to within 0·005 in of any one of the 253 standpipes. It carries two independent facilities, "normal" and "special." The latter is intended for use only when the reactor is shut down and at atmospheric pressure; by its aid, a broken fuel element could be inspected by closed-circuit TV, or the pieces of a broken element picked out and stored.

The normal facility, intended for on-load operation has a three-position magazine for shield plug, clean, and irradiated elements, and is also fitted with closed-circuit TV for continuous observation of the fuel passing in or out. It is capable of refuelling three fuel element channels per day under full load conditions; this rate can be exceeded when the reactor is shut down.

Closed-circuit CO_2 cooling for the irradiated element is built into the machine. When an irradiated element has been replaced and the channel plugged, the machine returns to one of three vertical transit tubes, down which the irradiated stringer is lowered.

The possibility of chemical action between water and fuel canning made the use of a cooling pond unacceptable, and

the elements are stored dry in a carousel. This consists of a drum 25 ft 6 in diameter, rotating about a vertical axis, and provided with 300 storage tubes on three concentric circles near its periphery. The drum, which weighs 60 tons when empty, has a maximum speed of one-fifth revolution per minute or, for inching, a peripheral speed of 6 in/min. By means of semi-

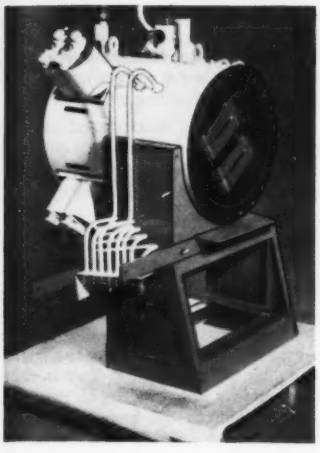


Fig. 19.—"Eight-in-one" burst fuel element detection unit under construction. *(Courtesy Plessey Nucleonics)*

automatic control, any of the storage tubes can be lined up with its appropriate transit tube.

The housing, 27 ft diameter and 21 ft 6 in high, is constructed as a pressure vessel of $\frac{3}{4}$ in thick plate, to withstand internal or external pressures of 2 psi, with a maximum leakage of 0·5% of the gross volume in 24 hours; it was also specified to tight dimensional tolerances.

Cooling of the elements in the carousel is by CO_2 at slightly above atmospheric pressure, the gas being recirculated through coolers with a heat-removal capacity of 568 kW. Three cooling circuits are provided, the load being normally shared by two, with the third as stand-by.

Fig. 20.—Lifting the top barrel ring of the pressure vessel into position during erection.

At the opposite side of the carousel, three further transit tubes are provided, through which elements, after an appropriate decay period can be removed for examination or forwarding to a reprocessing plant.

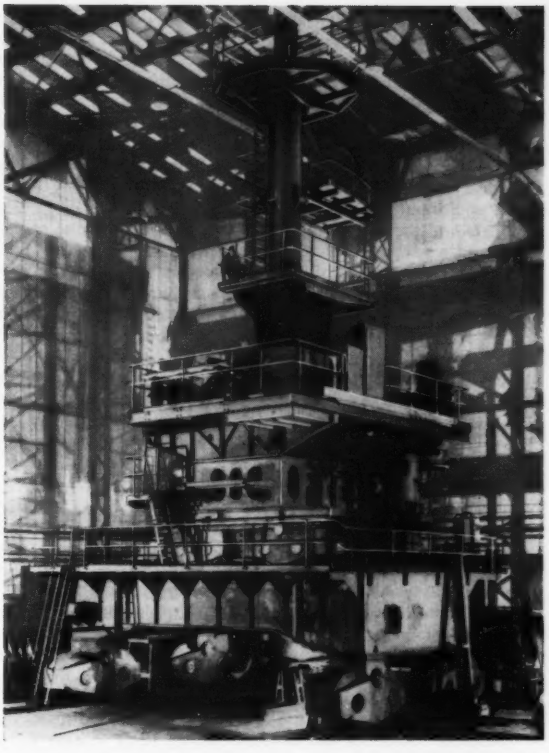


Fig. 21.—General view of charge/discharge machine under construction. *(Courtesy Markham and Co., Ltd.)*

Experimental Loops

Five of the fuel channels will be devoted to experimental loops, and are completely sealed from the main coolant circuit. Each has its own gas circulation and cooling arrangements, located in compartments immediately outside the shield at basement level. This will not only allow experimental work with different types of fuel element, but will enable variations to be made to the coolant composition. A re-entrant flow principle has again been adopted; gas flow is upwards past the fuel elements and down in the concentric annulus.

Instrumentation

Burst fuel element detection is provided for each channel. This is a development of the gas sampling fission product deposition

Fig. 22.—Standpipe extensions from top dome of vessel to charging floor.

technique widely adopted in U.K. reactors; but for the first time a matrix system is being employed. A 16 × 16 matrix of tubes in the core is necessary and these feed 32 precipitator units arranged in four banks of eight. By enclosing in one shielded pressure shell eight units with their own precipitators and counters but a common wire, it has been found possible to make the composite unit no bigger than the single units installed in, for example, Hinkley Point. Count rates are recorded and also brought out to an elaborate display board. Seven additional single precipitators serve the four experimental channels and the charge/discharge machine leaving one mobile spare and a reserve.

A permanent system of flux scanning is built into the core, comprising a system of 21 axial tubes through which argon gas at atmospheric pressure is passed, the flux being assessed by the induced A^{41} activity. Spatial variations in flux can be deduced by this means.

During sub-critical experiments, step changes in the strength of the neutron source can be made by inserting into the core a source Jerk Stringer. This contains two sources, one of which can be rapidly removed from the core volume by compressed air.

Considerable attention has been paid to temperature monitoring of the core and fuel element stringers. In all, 1 250 thermocouples are employed of which approximately 250 will provide a representative sample of fuel can temperatures, 200 record coolant gas temperatures at the outlets of the fuel channels, 250 in the graphite itself, whilst the remainder monitor the temperature of outside components of significance such as the biological shield. For following these temperatures, scanning equipment will be used which will check temperatures in sequence, compare them with preset values and raise the alarm should the set temperatures be exceeded. At the same time the actual temperature recorded and its position will be displayed. A complete record of the scanned information is also stored on a printed data sheet.

Turbines

Steam from the heat exchangers is fed to a 33 MW turbo-alternator which operates at 3 000 rev/min and generates electricity at 11·5 kV. The turbine is a standard two cylinder design with a single flow, high pressure cylinder of the impulse type followed by a low pressure cylinder of the double flow, outwards reaction type, with the exception of the first stage in each flow which is of the impulse type. Vacuum at maximum rating is 28·6 inHg with a final feed temperature of 350°F. The feed water heating is by means of steam bled from four points on the turbine although provision is made for supplying the high pressure heaters direct from the heat exchangers.

Cooling water of the condensers is recirculated through cooling towers capable of handling 1·75 million gal/h of water. These are of the induced draught type, an air flow of 851 000 ft³/min being maintained by four 26 ft diameter fans driven by 140 h.p. electric motors.

Site Progress

Major constructional work on the plant is now complete and commissioning of various sections has begun. It is anticipated that fuel loading will begin in the next few weeks and that the reactor will go critical in mid-summer, leading to full power operation by the end of the year. Only limited time need be spent on physics experiments at low power because these can be simulated in Hero. Control problems will have been simplified by the adoption of stainless steel canning and the reactor will be able to press forward on its programme of fuel element testing almost directly.

Acknowledgement

We are indebted to Ace Film Productions for the illustrations to this article, all of which, unless otherwise stated, are stills from the film they have made on AGR.

PRELIMINARY LIST OF CONTRACTORS

Acheson Colloids, Ltd.
Graphite.

W. H. Allen, Sons and Co., Ltd.
Diesel standby sets.

Babcock and Wilcox, Ltd.
Centre biological shield; reactor containment building; airlocks.

N. G. Bailey and Co., Ltd.
General electrical installation.

J. Blakeborough and Sons, Ltd.
Main gas valves and operating mechanisms.

Broom and Wade, Ltd.
Air compressor.

John Brown (SEND), Ltd.
Upper refuelling tubes; refuelling machine.

Brush Electrical Eng. Co., Ltd.
6 MVA transformers.

Burnett and Lewis, Ltd.
Gas driers.

Chloride Batteries, Ltd.
D.C. battery.

Cockburn's, Ltd.
Gas safety valves.

Constructors John Brown, Ltd.
Erection and operation of 130-ton guy derrick. Main contractor for reactor instrumentation, main reactor control room panels.

Darlington Forge Ltd.
Cambered duct rings for pressure vessel.

Davenport Engineering Co.
Cooling towers.

Dewrance and Co., Ltd.
Ancillary CO_2 valves.

Elliott Bros. (London), Ltd.
Control rod mechanisms; frequency convertor sets and ancillary equipment; emergency shutdown equipment.

English Electric Co., Ltd.
Turbine and feed heating plant; 33 kV switchgear.

Ericsson Telephones, Ltd.
Telephones.

Evans Lifts, Ltd.
Turbine building lift.

Ewbank and Partners, Ltd.
Turbine hall consultants.

Fairleede Eng. Co.
Graphite restraint gear.

Ferranti, Ltd.
750 kVA transformers.

Fischer Bearing Co., Ltd.
Graphite support bearings.

Fleming Bros., Ltd.
Structural steelwork for reactor and turbine house.

Flight Refuelling, Ltd.
Refuelling branch latch mechanisms.

General Electric Co., Ltd.
Motor-alternator sets.

Hadfields, Ltd.
Control rods.

Matthew Hall and Co., Ltd.
Main heating and ventilation of containment vessel.

Henry Hargreaves, Ltd.
Inner shield cooling plate work.

Harland and Wolff, Ltd.
Graphite support plates.

Hick, Hargreaves and Co., Ltd.
Vacuum pumps, dump condenser.

Hopkinsons, Ltd.
Ancillary CO_2 valves; steam and feedwater valves.

J. Howden and Co., Ltd.
Main CO_2 circulators.

ICI (Metals Division)
Wrought beryllium.

Imperial Chemical Industries, Ltd.
CO_2 storage plant.

International Combustion, Ltd.
Heat exchangers; inner gas ducts; carousel.

J. T. Kennicot
Feed line dosing.

W. Kenyon and Sons, Ltd.
Lagging in turbine hall.

Walter Kidde Co.
Fire protection equipment (CO_2).

Laurence, Scott and Electro-motors, Ltd.
Electrical work on main circulators.

London Transformer Products, Ltd.
1 000 kVA transformers.

Markham and Co., Ltd.
Refuelling machine.

Mather and Platt, Ltd.
Feedwater pumps; fire protection equipment (Mulsifyre).

Matterson, Ltd.
Cranes for fuel element building and in reactor.

Mitchell Eng. Co., Ltd.
Fuel transit station; mechanical daywork contractor.

Neckar Water Softener Co., Ltd.
Water treatment plant.

Newburgh Eng., Ltd.
Graphite restraint gear.

Newton Chambers and Co., Ltd.
Containment ventilation; chemical plant.

Pirelli, Ltd.
H.T. cabling.

Plessey Co., Ltd.
BFED equipment.

Plowright Bros., Ltd.
Annular shield.

A. Reyrolle and Co., Ltd.
11 kV switchgear; 415 V distribution boards.

John Smith (Keighley), Ltd.
Turbine hall crane.

Standard Telephones and Cables, Ltd.
Telephones.

Stewarts and Lloyds, Ltd.
CO_2 pipework, steam and feedwater pipework.

Switchgear and Cowan, Ltd.
Main 415 V switchgear.

John Thompson (Wolverhampton), Ltd.
Fuel element breakdown.

Vokes, Ltd.
Gas filters.

Wharton Crane and Hoist Co.
Main reactor crane.

Whatlings, Ltd.
Civil engineering contractor.

Whessoe, Ltd.
Reactor vessel, tundish, diagrid, hot box, inlet gas deflectors and thermal shield.

Whipp and Bourne, Ltd.
Main d.c. switchgear.

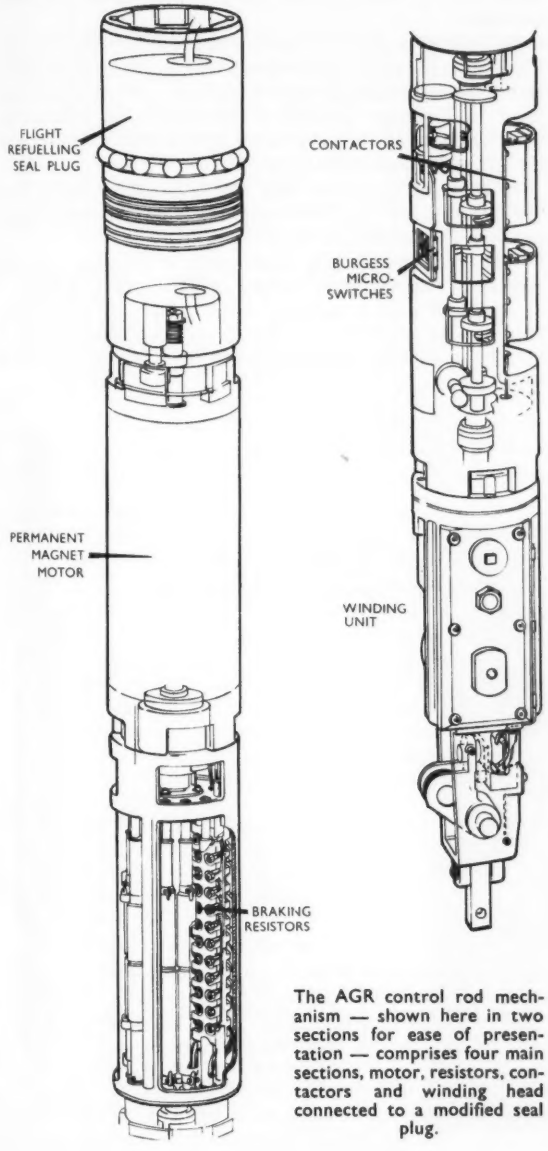
York Shipley, Ltd.
Refrigeration plant.

Control Rod Systems for AGR

By A. D. WRIGHT, B.Sc.
and
K. F. LEBEAU
(Elliott Bros. (London) Ltd.)

Although a control rod mechanism is basically a simple device for raising or lowering absorber rods the design and development of such a mechanism is complicated by operating conditions in the reactor and by the exceptionally high degree of reliability required. This article describes the main control and the auto control systems developed for AGR.

As the number of coarse control rods in AGR depends on the choice of fuel canning material—s.s. or beryllium—the system has been made sufficiently flexible to control up to 24 rods. Each mechanism comprises a motor-driven sprocket and chain supporting a boron steel control rod and extension piece weighing 285 lb which is raised or lowered through a height of 16 ft. The mechanisms are each contained in the top of a charge tube of $5\frac{1}{8}$ in bore in an atmosphere of carbon dioxide at a pressure of 270 psi and a maximum temperature at the motor of 150°C. This temperature is maintained by air cooling external to the containment tube. The maximum rate of withdrawal or insertion of the rods under normal operating conditions is 0·006 in/s and a fast insertion speed of 0·06 in/s is also provided.



The AGR control rod mechanism — shown here in two sections for ease of presentation — comprises four main sections, motor, resistors, contactors and winding head connected to a modified seal plug.

The auto-control mechanism is designed to use many parts common to the coarse mechanism for convenience of manufacturing and servicing. As there are functional differences, however, sections are arranged so that they cannot be interchanged and thus affect the operation of the other mechanism. The motor and control equipment for the auto-control mechanism are entirely different to the coarse control system.

The materials used in the construction of these mechanisms are those compatible with use inside the reactor pressure vessel. Generally, the materials are confined to stainless steels and in some cases mild steels. Tests in simulated reactor conditions for gas temperature pressure and dryness were carried out on working surfaces, bearings and on the chain.

Main Control Rod System

In order to ensure that the rods would respond precisely to control, a synchronous motor was required. The choice in the case of the coarse control rods lay between a low-speed synchronous reluctance type, and a permanent magnet type, both without brush gear. Adoption of the former type would have required the addition of a permanent magnet type of eddy current brake whereas in the latter case, by switching resistors into the motor circuit during free-fall conditions the motor could be used as a regenerative brake. The latter system was chosen.

The frequency converter and control equipment provide a 3-phase supply to the coarse control rod motors at selected low frequencies including zero frequency. Three frequency converters are supplied comprising a running set, a stand-by set and a spare.

The mechanisms in this system are made up of five sections comprising the winding unit, the chain casing, a sleeve valve, a control rod extension and the control rod. All these sections are housed in selected refuelling branches within the reactor pressure vessel. The control rod is supported by a duplex stainless-steel chain carried on a sprocket driven by the motor.

The winding unit incorporates the permanent magnet synchronous motor having insulating materials conforming to class "H" specification. This motor is coupled to the main shaft of the mechanism through a free-wheel, the purpose of which is to prevent backwinding of the control rod supporting chain under certain conditions. The main shaft transmits the motor torque to the driving sprocket shaft through bevel and spur reduction gearing.

The upper end of the motor is connected to the refuelling branch gas seal plug through which all electrical leads are

passed. The seal also houses an auto-lock drive unit which can be engaged with the motor-shaft through a 1 : 1 spur gear drive. A portable winding unit on the charge face to raise the control rod in the event of an electrical failure of a mechanism driving motor is also provided.

Below the driving motor is situated a bank of wire-wound resistors to provide a braking load to the motor during a free fall drop of the control rod. These braking resistors are connected by the operation of cam-operated contactors of special design. The operating cams are situated on shafts driven through reduction gearing from the main shaft.

There are two stages of braking before contact between control rod and impact stool is made. A synchro transmitter, which is used for rod position indication, is located above the two contactors; it is driven through a 1 : 1 spur gear driven from one of the camshafts used to operate the contactors. This transmitter is of special design and employs flexible ligament rotor connections and has class "H" insulation.

A pair of micro-switches are also operated by a further cam on one of the contactor operating camshafts. One of these micro-switches indicates when the control rod is latched in its top position, usually prior to removal; the other operates an interlock circuit.

The lower end of the winding unit houses the winding sprocket and slack chain roller assemblies. The latter unit actuates a micro-switch which gives an indication on the reactor control desk of loss of tension in the control-rod suspension chain.

The chain casing is suspended from the lower end of the winding unit by means of an articulated link arrangement. The duplex stainless steel chain, after passing over the winding sprocket and slack chain roller assemblies, previously described, passes down one side of the chain casing, over a pair of rollers, to position the chain on the centre line of the charge tube. The control rod and extension is attached to this run of chain by a quick-release ball coupling.

The principal materials used in the construction of this unit are suitable grades of stainless steel, with some hard chrome-plated mild steel. Graphite bearings are used for the sprocket assemblies in view of the high service operating temperature.

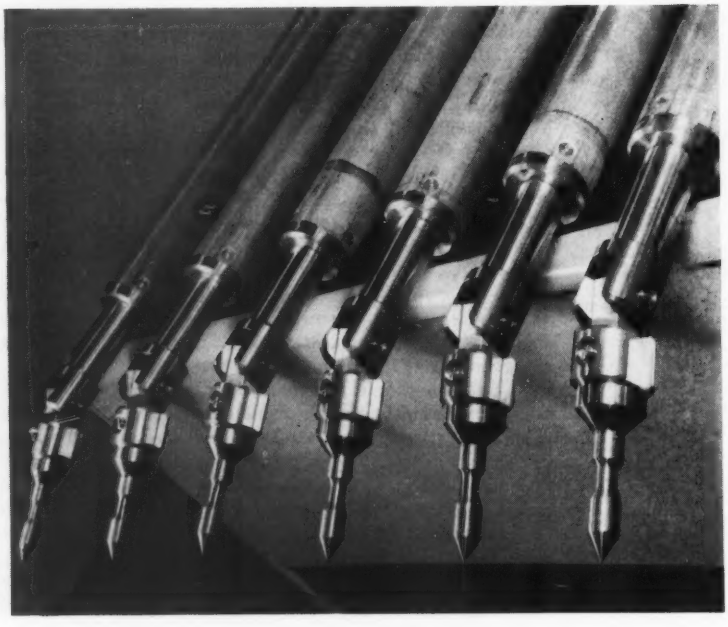
The sleeve valve acts as a gas flow restrictor and has six ports at its lower end positioned on the horizontal centre line of the reactor hot box. The ports are provided with screwed plugs which can be removed, as required, in order to regulate, within certain limits, the quantity of gas which is allowed to flow from the channel into the hot box. The sleeve valve is supported from the lower end of the chain casing by a ball-type sleeve coupling. This coupling permits a small amount of vertical misalignment between the two units.

The upper end of the section houses the mechanical ball latch assembly which is designed to support the weight of the control rod and extension during insertion and removal of the complete mechanism from the reactor. This latch is actuated by an annular ring on the neck of the control rod extension and will operate when the rod is raised to the full extent of its travel and lowered a few inches. It will automatically release if the rod is raised again and then lowered.

An extension piece to the control rod is provided, the upper end of which is connected to the supporting chain with a quick-release ball-type coupling. At the lower end there is a similar type of coupling with an additional universal joint feature to allow for misalignments between the extension and control rod proper.

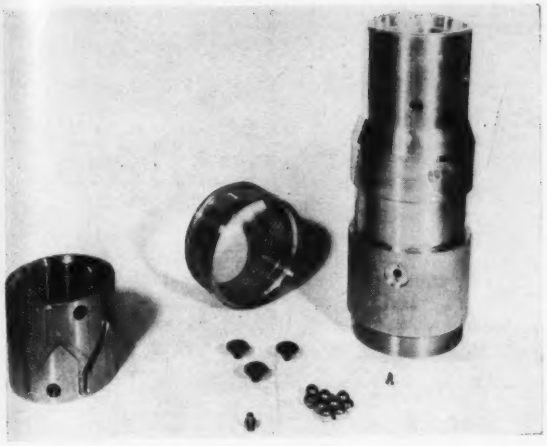
A telescopic feature is built into the unit, in order that the control rod and extension can be accommodated together within the transit facility.

Control of the winding unit motors is achieved through a variable low frequency supply. This supply is generated by means of a set comprising motor, generator and exciter mounted on a common bedplate, in conjunction with a variable-speed sine potentiometer. The d.c. exciter is used



The control rod extension units have universal joints to allow for misalignment.

The extension piece is telescopic so that the control rod and extension can be housed together in the transit facility.



Components for the automatic locking and quick release device which supports the control rod and extension.

to supply a sine potentiometer which has three wipers displaced by 120°. The output from this sine potentiometer is 3-phase a.c. with a frequency depending upon the speed at which the wipers are rotated.

The 3-phase sinusoidal output from the sine potentiometer excites the field coils of a special 3-pole generator. This generates a 3-phase rotating field at the output brushes and this supply drives all the rod motors simultaneously. There are three sets. One set is normally used on load, with a second set running on no-load as a standby. The third set can be used for special operations but is normally shut-down.

The output from any one of the three L.F. generators can be fed to one of three bus-bars, A, B or C. The mechanism motors can be individually selected to be supplied from bus-bars A or B, while C bus-bar is connected to a test load. In normal circumstances all mechanism would be fed from one bus-bar only, with one L.F. generator feeding the bus-bar.

Auto Control System

This system, which comprises three mechanisms and rods each together with control circuits, automatically maintains a set power level in the reactor. A manual control unit is also provided for each mechanism. In automatic operation the channel outlet gas temperature is compared with a reference signal of required temperature and any error signal is amplified in a pre-amplifier unit.

The manual control unit causes three control transformers to rotate at a selected speed. Any error signal between the mechanism synchro transmitters and the control transformers is fed to the power amplifier and used to actuate the mechanism.

Transistor circuits have been used throughout in the design of these amplifiers all of which are plug-in units with the exception of the power output amplifier, the transistors of which are mounted in a heat sink on the equipment chassis.

This mechanism is similar in construction to the coarse control mechanism, the major difference being the motor which, in this case, is a 2-phase a.c. induction type fed from a 50 c/s supply at 110 V. The drive from this motor is taken through a spur reduction gear and vertical shaft, then through a 2 : 1 bevel gear reduction to a horizontal shaft and then 1 : 1 spur gears to a further horizontal shaft on which is mounted the chain winding sprocket. A duplex stainless-steel chain is used to support the rod as in the main control system.

The construction of the mechanism is in four basic assemblies comprising the winding unit, the chain casing, the sleeve valve and the control rod. These are attached together and suspended in the refuelling tube from the gas seal plug. This gas seal plug is identical to those on refuelling tubes which house the main control rod mechanisms except that the mechanical drive shaft for emergency use is not provided in this case.

An electromagnetic brake is mounted above the hoist motor and coupled to it. This brake holds the rod through the motor in the event of failure of the reference phase supply to the motor. In this event the brake coil is energized from a d.c. supply which is automatically switched in by external means.

Rod position is indicated by a synchro transmitter driven from a camshaft through an Oldham coupling. The synchro is a high-temperature type with ligaments in place of slip rings. Five cams on this shaft operate high-temperature-type micro-switches housed in a compartment of the winding unit. These micro-switches indicate particular positions of the rod.

The normal operational travel of the auto control rod is confined to a central zone. If the lower end of the rod moves outside this zone, into what are termed the upper and lower warning bands of one foot depth, an external circuit is energized by two of the five cam-operated micro-switches. One switch operates for the upper warning band and one for the lower.

If the control rod travels farther into zones termed the upper and lower interlock bands another external circuit is energized by two more of the cam-operated micro-switches. The fifth micro-switch, termed the upper limit switch, is set to operate at a position corresponding to the control rod resting in the latched position.

The control rod attached to this mechanism is of tubular construction in stainless steel approximately 15 ft long weighing 80 lb with the upper third graphite filled.

Acknowledgements

Elliott Bros. (London), Ltd., acknowledge the close collaboration of members of the AGR Design Office during the development of these control rod systems. Acknowledgements are also made to Mather and Platt, Ltd., and Brookhirst Igranic, Ltd., who were responsible, respectively, for the manufacture of low frequency generation equipment and mechanism motors, and control panels and switchgear.

Elliotts provided a special clean conditions room for assembly of AGR control rod components.

Clean Conditions

G.E.C.'s nuclear clean workshop at Erith, Kent. The crane is about to lift a component from the reception bay into the assembly area.

An examination of the need for clean condition areas in nuclear manufacture covering both works and site assembly of reactor components.

WHAT is implied by the term "clean conditions"? Who lays down the rules and regulations for clean conditions assembly? And how necessary are clean conditions anyway? Most companies in the nuclear industry are faced with these questions at some time or another.

Strangely enough there are no rigid rules laid down by the Atomic Energy Authority. True, a manufacturer can expect guidance from the design office of a particular reactor project but in the main these instructions provide a negative approach—restrictions on the use of incompatible materials; emphasis on the need to exclude dust and foreign matter generally. Because of the lack of established standards interpretation of the terms "clean conditions" varies: a reactor design engineer quite naturally takes a more serious view than the small sub-contractor.

How necessary are clean conditions? *Nuclear Engineering* proposes to publish a series of articles outlining some of the more important requirements, and, at the same time, describing methods of ensuring that clean areas are clean. We also propose to publish, at a later date, a guide to manufacturers of equipment suitable for clean areas.

In general, all reactor materials must be compatible with the fuel element canning material. In order to prevent damage to fuel elements during reactor operation many materials must be rigorously excluded from the reactor gas circuit. Secondly, dust must be excluded because it might become radioactive and the activity would then be carried around the circuit. There is the additional objection to dust that it can damage over a long period moving parts located within the active circuit upon which maintenance is either difficult or impossible. Thirdly, any contamination of the circuit by fissile material will lead to the production of fission products which would decrease the efficiency of the BFED gear and so imperil the safe working of the reactor. Satisfying these conditions requires careful organization and strict control.

A clean area may be defined as a place for assembly, inspection, packing, erection, and maintenance of any item of plant for inclusion in the reactor gas circuit. The areas are sub-divided into works clean areas, reactor clean areas, semi-clean conditions and full-clean conditions.

Works clean areas are those set aside for the machining, assembly, cleaning, inspection and packing of all items of plant to be included in the reactor gas circuit.

If the clean area is to be constructed inside a shop already in existence, the immediately surrounding area should be declared "semi-clean" and should be kept as dust-free as possible. In constructing a special purpose building it is advisable to choose roof members that minimize the collection of dust or any other form of contamination.

Floors, if these are concrete, will be covered with an impervious material such as linoleum or treated with an anti-dust sealing compound. All corners where practicable will be rounded off to permit easy cleaning. Care should be taken in the placing of light fittings and conduits, and the walls of the clean area should contain a large proportion of glass. This will allow supervising staff to see into the clean area without actually entering. Walls should be smooth and free from any pipes or protrusions which may collect dust, and should be covered with approved paints free of incompatible materials.

The following materials are among those that must be excluded from entering a clean area: nickel; strontium; mercury; tin; lead; bismuth; cadmium; zinc; calcium; silver; copper; boron; aluminium; lithium; thallium; antimony; silica*; gallium; indium; cerium; praseodymium. All these materials are incompatible with Magnox and must not be allowed to be taken into any clean area.

The siting of the factory should be considered when the location of air filters is being decided, as obviously the air around a factory sited in a rural area will be much cleaner than a factory situated in a heavy industrial area. Generally, however, all air supplied to the clean area will pass through renewable media filters, capable of retaining all particles of a size greater than 10 microns. The air temperature in the clean area must be controlled so that the possibility of condensation in the area is eliminated. The clean area should be kept at a pressure slightly above atmospheric to prevent the ingress of dust from outside. Entry to, and exit from, the works clean area should be through an air lock.

Floors and walls of the clean area must be regularly cleaned by the use of vacuum cleaners. No brooms should be used unless they are attachments to vacuum cleaners.

Vehicles and other plant are not allowed to enter (and so contaminate) a clean area. All vehicles must be backed up to the entrance bay and unloaded on to trucks used exclusively in the clean area.

Special clothing consisting of overalls and, in some instances, caps and gloves should be provided for all personnel. The overalls should either have plastic buttons or, preferably, tapes for tying. No employee suffering

* Silica does not need to be in such intimate contact as other materials to cause damage.

from any form of contagious skin disease can be allowed to enter a clean area.

Work benches should be covered with a non-absorbent material such as plastic. Cross-bars near floor level hinder cleaning and they may also be used as foot rests, in which case dirt could be scraped off the shoes. No eating, smoking or drinking will be allowed inside a clean area.

Absolute cleanliness can only be achieved by establishing the order in which certain classes of work are passed to the clean room. For example, materials for shot-blasting should be first degreased, then shot-blasted before being passed to the clean area for assembly. Materials which do not require shot-blasting go through the main materials entry for degreasing and then straight into the clean area.

After processing in the clean room reactor components should be packed under full-clean conditions. Silica gel may be used as a moisture absorber. The components will then be packed in sealed polythene bags with the corners suitably protected against abrasion.

One of the most important features of all clean condition work is adequate supervision. The engineer in charge should be not only fully acquainted with the rules and conditions, but also personally aware of the absolute necessity for them. His aim should be to instil into all employees a knowledge of, and watchfulness for, any contamination.

As the ideas involved in clean conditions are not normal ones for most personnel, some time may be required to become completely familiar with the necessary rules; meticulous observation of such rules by the engineer in charge and by all supervising personnel will, however, serve as a necessary example.

Even with normal observance of the rules mistakes are possible; a check must be made on all materials brought into the clean room. For example, if it is necessary to change a set of tools or to bring in lubricating oil or grease for maintenance of overhead handling gear, careful inspection is necessary to ensure that contaminants are not brought in with them.

Entry to the clean area should be by way of an air lock and only one door should be open at any one time. Outer clothing must be removed and the special clothing donned in the change room. All personnel entering the clean area must observe the same precautions, irrespective of level or status, and no relaxation under pressure of authority, however high, can be tolerated. In most instances the entry to the clean area, depending upon the work being done, will be manned and a pass system introduced.

A semi-clean area may be defined as an area within a clean area where work such as welding, cleaning, etc., may be carried out, or the area immediately surrounding the clean area which is kept as clean as possible, thus assisting in the prevention of foreign matter entering the clean area.

Equipment Manufactured under Clean Conditions

It is not practicable to list all the items included in the gas circuit, and the following instructions are intended solely as a guide:—

Graphite. Machining, inspection and packing of the graphite blocks for the moderator must be carried out under clean conditions. The machining operation calls for special treatment in that the machines must have individual dust and swarf extractors.

Charge Pans. The charge pans will be degreased by dipping in an approved degreasing plant, and then shot-blasted (care being taken to use a compatible shot). No shot which has been previously used on any incompatible material may be used. The charge pans will then be protective coated, and packed in lined boxes for delivery to site.

BFED Tubing. Although it is not possible to manufacture the tubing under completely clean conditions, care is taken to ensure that no contaminating lubricants are used during the drawing process. During the manipulation semi-clean conditions are enforced, and all further work on the tubes (bending, packing, etc.) is carried out in the clean area.

Valves, Compressors and Precipitators. All equipment comprised of more than one part for inclusion in the gas circuit should be assembled and packed in the clean area.

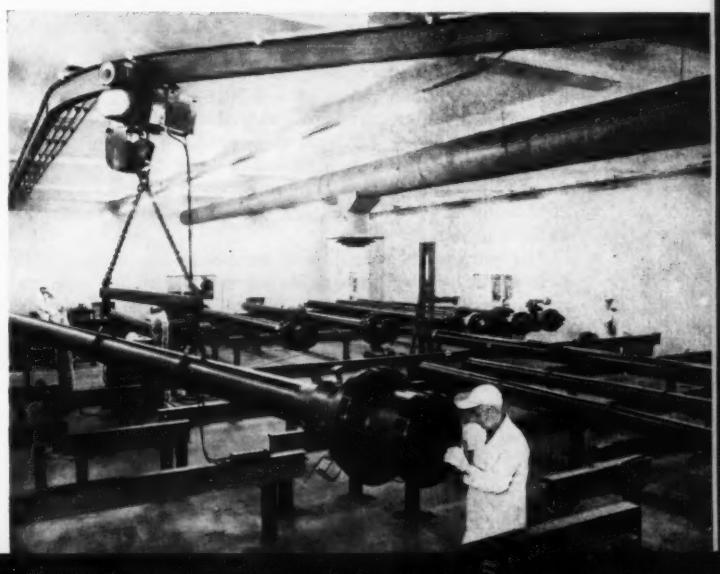
Ducting and Blower Casing. The ducting will not be shot-blasted and packed under clean conditions, but will be degreased and sent to site semi-clean. Prior to erection, the duct sections will be shot-blasted and coated with protective. After welding the weld will be wire brushed and recoated.

Boiler Tubes. Hitherto shot-blasting has been used for cleaning the boiler tubes for nuclear stations. The method proposed for Trawsfynydd, however, is ultrasonic cleaning in a fluid such as trichlorethylene. The results of considerable research work on this class of tubing have shown that this is the most satisfactory method of ensuring cleanliness. Samples of similar elements cleaned by this method have been tested by the Authority who have given their acceptance of the method for similar duties.

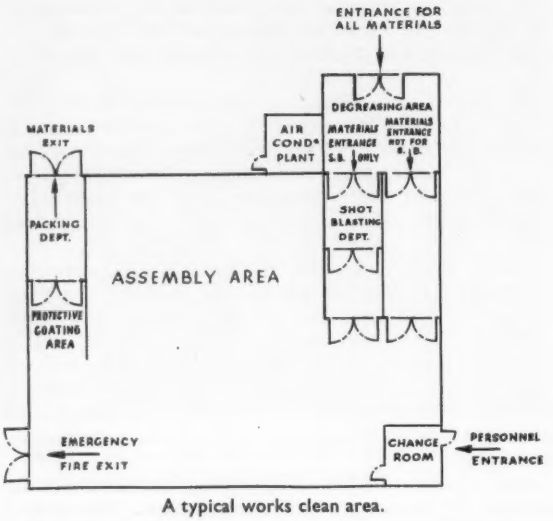
Control Rods. The control rods will be assembled in a clean area under full-clean conditions. During manufacture of the control rod casings, care will be taken to ensure that no incompatible lubricants are used. After cleaning and degreasing the tubes will be taken into the clean area annexe where the boron inserts will be placed into the tubes. The control rods will then be packed and sent to site.

Actuating Mechanisms. Actuating mechanisms, cables, closure units, E.S.D. and flux scanning heads, are all assembled in the clean area. During the manufacture of the parts care must be used in the choice of materials, equipment and tools to ensure that they do not come into contact with incompatible materials.

Shield Plug and Heat Baffle. These items should be degreased, shot-blasted and coated with protective before delivery to site. When shot-blasting is employed for cleaning castings and fabrications, all traces of shot must be removed before applying a protective coating. Possible methods of removal are wire brush, air blast or vacuum. An inspection should be carried out after the dust removal and before the coating to make sure that all traces of shot have, in fact, been removed.



Standpipes for Hunterston being assembled under clean conditions at Stewarts and Lloyds Tolcross works.



A typical works clean area.

So much for works clean areas which are comparatively easy to install and maintain. We turn now to clean areas on the reactor site—a far more difficult proposition. On completion of stress relieving, pressure testing of the reactor pressure vessel and subsequent cleaning, and for the duration of subsequent erection within the pressure vessel clean conditions must be established.

The temporary walls or partitions necessary for the construction of the clean area outside the vessel may be of hardboard or thoroughly dried plywood and free from contamination, the joints being sealed with boron-free tape. External walls will be of a substantial nature, adequately protected from the weather and dust and damp proof.

An air conditioning plant will supply air through renewable media filters to the clean area. Stand-by equipment for the air supply and lighting within the clean area will ensure continuity of operation.

Canteen facilities and toilets will be located in a semi-clean area within the clean area. The canteen mess room will have an extractor fan for drawing away the smoke and steam which may be present during meal breaks and this fan will discharge outside the clean area. All personnel entering this semi-clean area must wear overshoes which are removed on entering the clean area.

Special clothing, regularly laundered, will be provided for all personnel entering the clean area. A complete change of clothing comprises: overalls; vest; shirt; underpants; socks; shoes; light gloves and cap. The overalls will have tapes instead of buttons and the shoe laces will have no metal tips.

All cleaning within the clean area will be by vacuum cleaners, no brooms being permitted unless such brooms are attachments of the vacuum cleaners.

The clean conditions established fall into two categories—semi-clean and full-clean.

Semi-clean conditions are established immediately after the pressure vessel has been cleaned down and protective coated. Under these conditions it is possible to do welding and various jobs which cannot be done during full-clean conditions, although at all times vacuum cleaners are provided for regular use.

The purpose of establishing semi-clean conditions is to keep the ingress of foreign matter to a minimum until the more exacting requirements of full-clean conditions are enforced. A pass system will be introduced and change-room attendants will issue a change of clothing to any personnel entering the semi-clean area. This change of clothing will comprise overalls, hat, gloves and shoes only.

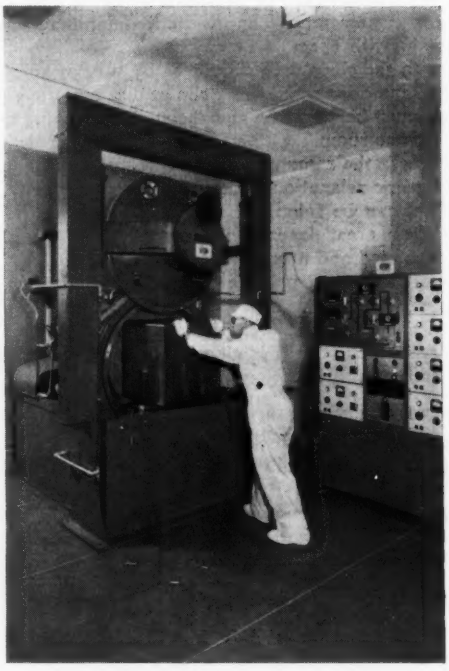
CO_2 fire extinguishers will be placed at strategic points and fire precaution notices will be placed close by. Telephones and alarms will be connected and first aid boxes placed in the clean area complete with stretchers. All precautions will be taken to ensure the safety of personnel working in the clean area. One of these features will be to include kick-out escape panels in the temporary walls of the clean area outside the pressure vessel. It should be noted that lint, bandages or ointment containing borax or boric acid cannot be provided in the first aid box in a clean area.

After stress relieving is complete cleaning of the reactor pressure vessel will be carried out by shot-blasting from the top of the vessel to the bottom. During this operation down-draught fans will be operating. One shift will shot-blast and the following shift will vacuum clean and paint protective coating. By carrying out the cleaning of the vessel in the alternate shift method the protection of the vessel will be ensured as the protective coat will be applied immediately after the shot-blasting.

To ensure cleanliness during fitting out a temporary clean area is also constructed at the top of the boilers and filtered and temperature-controlled air is supplied to the bottom of the boiler throughout the fitting-out period. The cleaning down of the boilers, ducting and blower casings will follow the same procedure as that described previously for the reactor pressure vessel.

Before entering the reactor or boiler clean area all personnel must be in possession of a pass issued by the resident engineer or his nominee.

On arrival at the clean area personnel will produce the clean-area pass to the change-room attendant who will issue a key to the locker into which the personnel will



At Cardonald, Glasgow, Cockburns Ltd., have recently commissioned an ultrasonic and vacuum plant for clean assembly. Valves and fittings are here being loaded into an autoclave.

deposit their clothing. After stripping off shoes and outer clothing (depending on the degree of cleanliness in force) personnel can enter the clean area. The attendant will make an inventory of personal effects (handkerchiefs and spectacles are the only personal effects allowed into the clean area). An inventory will also be kept of all hand tools, and small stores, i.e., nuts, bolts, etc. After the inventory has been taken personnel will then pass through an air lock to the clean change room.

On exit from the clean area personnel go through the same procedure in reverse and the attendant must check that they have still got their personal effects and hand tools, etc., listed in the inventory, before leaving the clean area. No smoking, eating or drinking will be allowed in the reactor clean area except in the canteen mess room.

At Trawsfynydd, for example, all materials will enter the clean areas through the east shaft on the south of the reactor building. The graphite blocks will arrive at the entrance to east access shaft in closed vans, which will reverse into the covered entrance and the access doors will be opened. The pallets of blocks will then be stacked into the lift and will be taken up to the 53 ft level, where they will be passed through a hatch into the carton disposal room, and then on to the final inspection bay where they will be stored ready for entry to the vessel.

All metal parts should enter the clean area through the east access shaft to be taken up to the 75 ft level. After removal of protective packing the parts will then be lowered into the clean area where they will be inspected and stored prior to entry to the vessel.

The following equipment will be installed in the reactor vessel under semi-clean conditions: pressure vessel insulation, levelling plates, and gas seals (lower parts).

Immediately prior to the installation of the graphite full-clean conditions will be initiated and persons entering the pressure vessel will then make a complete change of clothing. The following equipment is installed under full-clean conditions: graphite; restraints; main gas seal top plates; charge pans; and all BFED pipes inside the pressure vessel.

Semi-clean areas will be established in the two BFED rooms. The main purpose of this will be to eliminate draughts during the brazing of the BFED pipes in the galleries and rooms and to restrict access into these areas. During the installation of the instruments in the main control room semi-clean conditions will be enforced and all personnel entering the control room during this period will change into clean overalls and wear overshoes. Semi-clean areas will be set up for the erection of the charge/discharge machine in the charge machine maintenance bay and on the charge face for the insertion of the shield plugs, heat baffles and control rod assemblies.

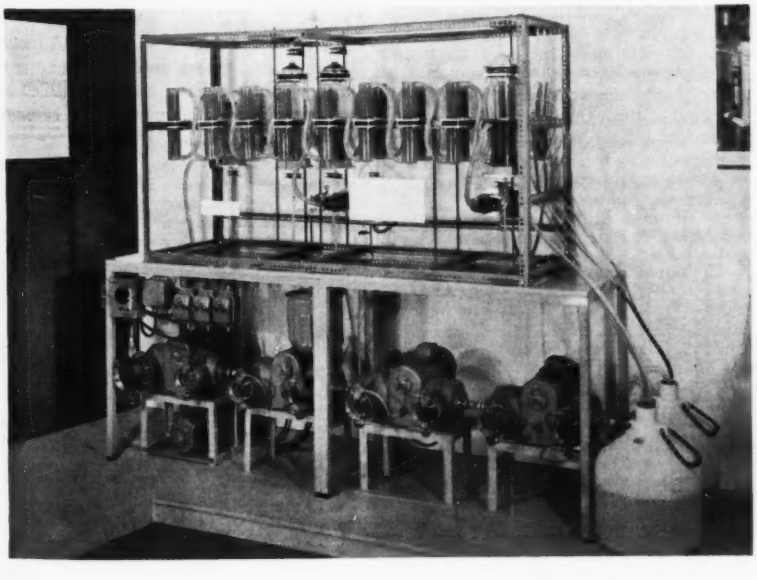
ASEA Separation Column

Swedish Process Plant for Reactor Fuels

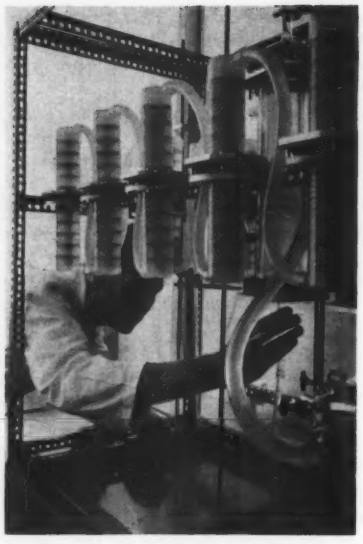
CAPABLE of processing five tonnes of uranium a year, a "table-size" purification plant for reactor fuels has been designed by Dr. Olle Lindström and chemists of the Section for Fuel Processing, at the Nuclear Power Department of Allmänna Svenska Elektriska Aktiebolaget (ASEA) at Västerås, Sweden. It is based on the familiar organic solvent liquid-liquid extraction process, the apparatus consisting of a chain of series-coupled tubes each containing stages separated by perforated bottom plates. Being more compact and less expensive than the plutonium separation plants so far built, it could lead to substantial reductions in the cost of refining uranium and plutonium.

The cost of treating irradiated fuels is high because of the heavy shielding required and the extensive use of remote handling techniques; total plant investment is roughly proportional to the volume of the shielded process. To cut plant costs, and thus reprocessing costs, this volume must be reduced by employing more compact equipment.

Originally, suitably packed extraction columns up to 20 m in height were used for passing through the aqueous and organic liquid phases counter-currently. The use of pulsed columns made possible a reduction by about one-half of the height of the columns and in these the liquids were forced to and fro through sieve plates by means of a pulse pump. Mixer-settlers, which require less head room but more floor area than pulsed columns, have also been employed. Here the two liquids are mixed in one chamber and separation takes place in a second. Such units are arranged in series as a battery, the two process streams running counter-currently. For highly active processing,



Swedish pilot plant for the refining of 5 tonnes of uranium a year, involving extraction, scrubbing and stripping of uranium solutions with a single pulse pump.



Opening the outlet valve on the transfer unit.

the additional fluid handling with the mixer-settler technique is a disadvantage.

The ASEA column is designed to combine the compactness of the mixer-settler with the simplicity of the pulsed column. The result can be regarded as a conventional pulsed column which has been cut into shorter column elements connected in series by single transfer lines. To pass the lighter component from the top of one element to the bottom of the succeeding element and the heavier component in the opposite direction (the reverse of the normal flow of the liquids in the column), each element is operated as a self-contained extraction unit with internal separation of the two phases. The movement of the liquids between the column elements is controlled by a pulse pump. The volume displaced in one full stroke of the pump should be of the same order of magnitude as the volume contained in the transfer line between the elements. Each stroke forward in the column displaces liquid enriched in the lighter component through the transfer line, whereas each reverse stroke pushes the heavy phase back to the foregoing element.

Employing two pulse pumps may be an advantage, with one delivering a low frequency and large amplitude stroke to effect the movement of the process fluids while the other is adjusted to produce the optimum conditions of the extraction process itself. This method is particularly valuable when a comparatively small number of longer column elements is preferred to a large number of short column elements. The use of two pumps also gives complete freedom in the accommodation of the column in a given geometry, e.g., in an available cell of an existing fuel processing plant.

Although the extraction operation is the same as in a conventional pulsed column the technique gives greater flexibility as the number and dimensions of the column elements can be varied at will and modifications are easily made, such as new column elements added to an existing battery. Especially with larger installations, the transfer lines also assist redistributing and minimize channelling in the column sections. With the connected shorter elements the hydrostatic pressure exerted on the pulse pumps is much smaller than in the case of straight column equipment.

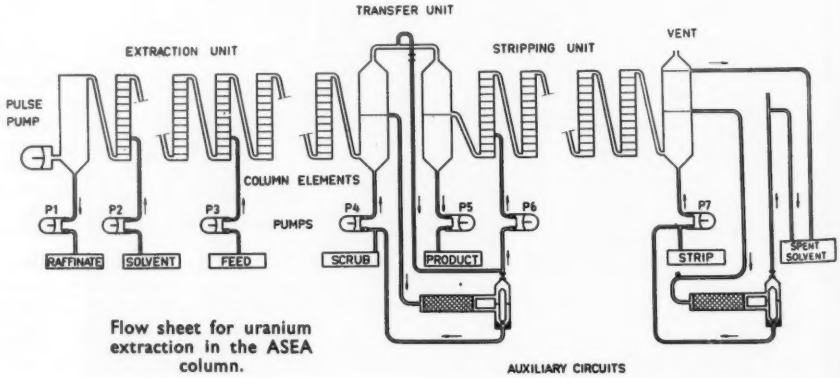
The ASEA column can be operated entirely automatically and interruption of operation does little harm as separation takes place only within the column elements, whereas in a conventional column a long period is necessary before equilibrium conditions can be re-established once the flow has been interrupted. Another novel feature is its auxiliary circuit for level control and removal of "crud"—an emulsion layer with suspended solids produced by the accumulation of impurities at the interface which affects the separation seriously.

Level control of the interface in the disengagement section of pulsed columns is important as the entire operation is governed by the position of the interface. Manometric dip tubes monitor the position of the interface in many process plants, the differential pressure between the tubes regulating the addition or removal of the process solutions to maintain steady state conditions. Because of the accumulation of crud, column operation has to be interrupted from time to time for clean-up.

In the ASEA column, however, the crud problem is eliminated and a simple and reliable level control obtained in the same operation; the principle of this is illustrated in the accompanying flow sheet. An outlet pipe is located where the interface is to be in normal operation (see, for example, the disengagement section of the stripping unit) and crud is continuously removed with the small flow of liquid through this outlet which passes to a filter unit with an attached separation chamber equipped with a float valve sensitive to the position of the interface in the separation chamber. The addition of the heavier component (the strip solution) to the column by means of a proportioning pump (P7) is offset by the controlled removal of heavy phase product by P5 which has a smaller capacity than P7. The difference in capacities between P7 and P5 causes an increase in the hold-up of heavy phase in the column and in the disengagement section. When the heavy phase reaches the outlet pipe it overflows into the auxiliary circuit and accumulates in the separation chamber. At a certain level of heavy phase in the separation chamber, the float valve opens with the heavy phase flowing out for reintroduction into the column, or, alternatively, for waste disposal. Thus, the difference between input and output gives rise to a differential flow through the auxiliary circuit. Pumps can also be used directly in the auxiliary circuits (as with the transfer unit shown in the flow sheet).

In the ASEA column a number of extraction processes can be conducted in series with no intermediate hold up tanks, etc. The use of a special transfer unit makes possible a continuous flow of liquids through a combined unit incorporating extraction, scrubbing and stripping, plus solvent cleaning (not shown), the pulsing movement being transferred through the entire column battery, in the example, via the organic overflow with no mixing of the two aqueous streams. Air is by-passed by a separate line from the highest portion of the organic solvent transfer line. The organic solvent is passed continuously, with no intermediate tanks, through the extraction, scrub and strip sections and is contacted by the various aqueous solutions involved, one after the other. The whole battery is operated by the main switch for the proportioning pumps and comparatively large variations in the pump rates can be tolerated due to the margins involved in the level control.

Work is continuing in the ASEA laboratory with a view to further improvements of the column and its application to uranium refining and plutonium recovery.



Flow sheet for uranium extraction in the ASEA column.

TRANSLATIONS

A Résumé of Principal Articles

Les céramiques dans la construction nucléaire —Conductibilité thermique. (138)

A la suite des résultats satisfaisants obtenus lors de l'utilisation du dioxyde d'uranium dans les réacteurs, les constructeurs sont de plus en plus intéressés par l'utilisation des céramiques dans les piles nucléaires. La présente série d'articles a été préparée par le département des céramiques du centre de recherche nucléaire C. A. Parsons and Co., Ltd., Newcastle. Les principales propriétés des matériaux céramiques intéressants sont décrites ainsi que les moyens par lesquels ces propriétés peuvent être améliorées. Le premier article a principalement trait à la conductibilité thermique. Dans les articles qui suivront, les propriétés mécaniques, la stabilité sous irradiation, la résistance aux chocs thermiques seront discutées.

Le transfert de chaleur par les surfaces rugueuses. (144)

En vue de l'utilisation de l'acier inoxydable comme matériau de gaine, dans les réacteurs réfrigérés au gaz, les propriétés de transfert de chaleur de différents types de gaines ont été sérieusement étudiées. Plusiers profils différents a été analysée et le type adopté pour AGR comporte une série d'anneaux concentriques de 0.2 mm de hauteur, de 0.2 mm de largeur disposés tous les 2.3 mm. Les caractéristiques de transfert de chaleur obtenues lors des essais sont décrites.

Les effets de l'irradiation par neutrons sur le béryllium. (149)

Sous irradiation, il y a non seulement altération du réseau cristallin du béryllium, processus caractérisant l'irradiation des solides, mais également des dégâts dûs à la formation d'hélium par transmutation d'atomes de béryllium par neutrons rapides. Lorsque la dose est augmentée, il en résulte que non seulement les propriétés mécaniques se trouvent modifiées, mais il y a également formation de bulles d'hélium. L'étendue des dégâts mesurée sur des éprouvettes dans des réacteurs de recherche est passée en revue en tenant compte des renseignements les plus récents disponibles sur ce sujet à l'heure actuelle.

Le Réacteur de type avancé A.G.R. (151)

A Windscale, le réacteur A.G.R. est en voie d'achèvement. Les essais de criticalité débuteront au commencement de l'été. Le projet initial a subit de nombreuses modifications, l'une des plus importantes étant la décision d'utiliser, pour la première charge tout au moins, des éléments de combustibles gainés à l'acier inoxydable.

Les caractéristiques d'A.G.R. diférent à de nombreux égards de celles, classiques maintenant, des réacteurs du type Calder Hall. Ces caractéristiques sont examinées en détail et sont représentées sur le dépliant inséré dans le journal. La construction des éléments de combustible, les particularités du chemin suivi par le gaz de réfrigération à la traversée du coeur, l'utilisation de gaines de circulation du gaz réfrigérant annulaires concentriques de même que le système de contrôle, le système de détection des éléments de combustible défectueux, etc. sont examinés successivement.

Keramische Stoffe in der Atom-Technik— Warme-Leitfahigkeit. (138)

Nachdem U'andioxyd sich als Reaktoren-Brennstoff eingeführt hat, ist das Interesse unter den Konstruktören von Reaktoren an der Verwendung von keramischen Stoffen in Kern-Reaktoren gestiegen. In der vorliegenden Artikelreihe, die von dem Stab der Keramischen Abteilung der Atomkern-Forschungs-Zentrale der Fa. C. A. Parsons and Co. Ltd., Newcastle, verfasst worden ist, ist alles zusammengestellt worden, was man über die Eigenschaften der in Frage kommenden Materalien jetzt weiss, und es werden die möglichen Verfahren diskutiert, mit denen man diese Eigenschaften verbessern kann. Der erste Artikel befasst sich in der Hauptsache mit der Wärme-Leitfähigkeit.

Warme-Uebertragung an aufgerauhten Flachen. (144)

In der Annahme der späteren Verwendung von rostfreieem Stahl als Material für die Ummantelung in gas-gekühlten Reaktoren, ist bereits beträchtliche Vorarbeit hinsichtlich der Wärme-Uebertragung durch die Mäntel der Brennstoff-Elemente geleistet worden. Eine Anzahl von Profilen sind untersucht worden, und der Typ, der für die AGR adoptiert wurde, besteht in einer Serie von konzentrischen Ringen 0,2 mm hoch und 0,2 mm stark, mit einem jeweiligen Unterschied von 2,3 mm. Die Wärme-Uebertragungs Charakteristik, die von Versuchsanordnungen abgeleitet werden konnte, ist beschrieben.

Die Wirkung der Bestrahlung von Beryllium mit Neutronen. (149)

Wenn Beryllium bestrahlt wird, dann ist es nicht nur die Schädigung, die das Gitter erfährt, die für alle Strahlungsverfahren charakteristisch ist, sondern die Schädigung, die durch die Bildung von Helium entsteht infolge der Transmutation der Beryllium-Atome durch schnelle Neutronen. Das Endresultat ist dann, dass mit Verstärkung der Dosis sich nicht nur die mechanischen Eigenschaften ändern, indem die Dehnbarkeit beträchtlich leidet, sondern, dass sich Heliumblasen bilden. Es wird eine Uebersicht über die Grösse der Schädigung gegeben, wie sie bei Versuchen an Mustern in den Forschungs-Reaktoren gemessen wurde, und es werden dann noch die allerneuesten Informationen über diese Frage gebracht, die jetzt zur Verfügung stehen.

Der verbesserte gas-gekuhlte Reaktor. (151)

Der Bau des verbesserten gas-gekühlten Reaktors in Windscale nähert sich dem Ende, und die Versuche für das Kritischwerden sollen im Anfang des Sommers beginnen. Seit dem ersten Entwurf sind eine Anzahl von Aenderungen in der Konstruktion gemacht worden, worunter eine der wichtigsten die Entscheidung war, Elemente in rostfreien Stahlmänteln als komplette Charge, zum mindesten für die erste Ladung zu verwenden.

Die Konstruktion des Reaktors unterscheidet sich in vieler Hinsicht von den bereits allgemein bekannten Prinzipien der Calder Reaktoren, und diese sind in einigem Detail in der anliegenden auseinander faltbaren Darstellung gezeigt, um die Wirkung der verschiedenen Komponenten zu erklären. Die Konstruktion der Brennstoff-Elemente, die Art des wiederholten Umlaufs des Gases durch den Kern, die Verwendung von ringförmigen Kanälen sind diskutiert, ferner das Kontroll-System, die Ueberwachung der Brennstoff-Elemente für Risse usw.

La Cerámica en Ingeniería Nuclear — Conductividad Térmica. (138)

Con el dióxido uránico establecido como un combustible para reactores hay un creciente interés entre los diseñadores de reactores en el empleo de la cerámica en los reactores nucleares. En la presente serie de artículos, preparada por el personal de la Sección Cerámica del Centro de Investigaciones Nucleares de C. A. Parsons and Co., Ltd., de Newcastle, se han recopilado datos sobre las propiedades de los materials cerámicos pertinentes, y se discuten los posibles medios por los que dichas propiedades pueden ser mejoradas. El primer artículo trata mayormente con la conductividad térmica. En futuros artículos se discutirán las propiedades mecánicas, la estabilidad de irradiación y la resistencia al choque térmico de los materiales cerámicos.

Transferencia de Calor en Superficies Desbastadas. (144)

En anticipación del uso del acero inoxidable como un material de enfundadura en los reactores enfriados por gas, se ha hecho considerable trabajo sobre las propiedades de transferencia de calor de las fundas de los elementos de combustible. Se han examinado diversos perfiles y el tipo adoptado para el AGR comprende una serie de anillos concéntricos de 0,2 mm. de alto y 0,2 mm. de ancho en un paso de 2,3 mm. Se describen las características de transferencia de calor que han sido derivadas de los aparejos experimentales.

El Efecto de Irradiación Neutronica Sobre Berilio. (149)

Bajo la irradiación el berilio está sujeto no solamente al estopeo de la red que es característica de todos los procesos de irradiación sólida pero también a los estropeos resultantes de la formación de helio mediante la transmutación da atomos berílicos por neutrones rápidos. El resultado neto es que conforme es aumentada la dosis, no solo cambian las propiedades mecánicas con una notable caída en ductilidad sino que también se forman burbujas de helio. Se pasa en revista el monto de los estropeos según medido en muestras en los reactores de investigación y se incluyen los últimos datos sobre asunto que ahora se hallan disponibles.

El Reactor Avanzado Enfriado Por Gas. (151)

El Reactor Avanzado Enfriado por Gas en Windscale se está acercando a su terminación y las pruebas de criticalidad comenzarán en los primeros días del verano. Desde su primera concepción, se han hecho diversos cambios en el diseño, siendo el no menos importante de ellos la decisión de instalar una carga completa de elementos revestidos en acero inoxidable, por lo menos para la primera carga.

El diseño del reactor difiere en muchos respectos de los ahora familiares principios de los reactores de Calder y se discuten estas diferencias en algún detalle como explicación adicional de las funciones de los diversos componentes mostrados en el dibujo que se acompaña. La construcción de los elementos de combustible, la norma de flujo reentrante del gas a través del núcleo, el uso de conductos anulares son todos discutidos, así como también el sistema de control, la supervisión del elemento defectuoso de combustible, etc.

Personal

Appointments—U.K.

Mr. R. V. Melville, geologist with the Geological Survey and Museum, Kensington, as scientific attaché to the British Embassy in Paris.

Mr. K. Maddocks, as chief project engineer of Yarrow and Co., Scotstoun. For the past five years Mr. Maddocks has been senior design engineer of the Yarrow-Admiralty Research Department, seconded to the AEA at Harwell and Winfrith.

Mr. K. A. Robinson, chief engineer of Lancashire Dynamo Electronic Products, to the board of directors.

Mr. P. J. Daglish, formerly manager of the English Electric aircraft equipment division, to the board of D. Napier and Son.

Mr. P. H. R. Lanem, head of the members' service department of the British Welding Research Assn., as the first director of research of the Drop Forging Research Association.

Mr. R. P. Newman, in charge of fatigue research at the British Welding Research Association, as head of the members' service department. His successor in the fatigue research department is **Mr. T. T. Gurney.**

Mr. Richard Adams, as general manager of the newly created Castrol engineering division. Before joining the company in July, 1960, he was manager of the mechanical and electrical engineering division of George Wimpey and Co.

Mr. R. Catherall, director of Solartron Research and Developments, to the board of the Solartron Electronic Group with responsibilities for research and development; **Mr. L. Malec,** managing director of Solartron Radar Simulators, to the parent board with responsibilities for system sales; and **Mr. H. D. Binyon,** director of Solartron Laboratory Instruments, to the main board as director of products sales.

Mr. James Oldroyd, BEAMA secretary since 1952, as general manager of the Lead Development Association.

Mr. A. Crockett, works manager of the Brooke Tool Manufacturing Company, Birmingham, to the board; and **Mr. J. Lamb**, chief accountant, to the board of the subsidiary, Brooke Tool Automation.

Mr. R. V. Melville.

Dr. P. Balligand.

Mr. W. A. de Haas.

Prof. F. Forward.

Viscount Amory of Tiverton, to the board of the Steel Company of Wales.

Mr. J. W. Haig-Ferguson, divisional director in charge of electronics, Bruce Peebles and Co., as managing director of R. and J. Beck, the optical instrument manufacturers.

Mr. E. T. Card as a director of Electrothermal Engineering.

To provide for future expansion of the company, Livingston Laboratories have extended their board, which now comprises **Mr. G. F. Livingston Hogg** (chairman and joint managing director), **Mrs. M. R. Hogg, Mr. H. Sellers** (joint managing director), **Mr. S. W. Urry** and **Mr. F. R. G. Webb.**

Mr. K. Clark, as assistant export manager of Acheson Colloids, a subsidiary of Acheson Industries.

Overseas

Dr. Pierre Balligand, head of the large research reactors division of the CEA, France, as deputy director-general of the IAEA in charge of technical operations. He succeeds **Dr. Hubert de Laboulaye,** who is to return to a senior position with the CEA.

Mr. W. A. de Haas, secretary of the Reactor Centrum Nederland industrial commission, as chairman of the newly formed Netherlands Atom Forum (see "World Digest").

Dr. T. J. Thompson, professor of nuclear engineering, Massachusetts Institute of Technology and director of the MIT reactor project, has been elected chairman of the U.S.AEC advisory committee on reactor safeguards for one year. He succeeds **Dr. Leslie Silverman,** professor of engineering in environmental hygiene at Harvard University.

Dr. Elda E. Anderson, in charge of health physics education and training at Oak Ridge, has been appointed chairman of the American Board of Health Physics. The purpose of this board, created last year, is to establish uniform standards for radiation protection specialists.

Professor Frank Forward, head of metallurgy and mining at British Columbia University, in charge of the recently formed Canadian Uranium Research Foundation.

Dr. Walter J. Stromquist, in charge of plant systems engineering at Alco's nuclear engineering department, Schenectady, as resident manager of the SM-1 at Fort Belvoir.

Mr. Douglas E. George, as director of the U.S.AEC division of nuclear materials management. He has been acting director since September, 1959, when **Mr. Donald Musser** was appointed as U.S. technical adviser to the Geneva disarmament conference.

Mr. James D. Moore, plant manager at the Salt Lake City works of Vitro Chemical, as manager of Western Operations.

Mr. Paul O. Morton, project engineer for the Nuclear Power Group (U.S.), and **Mr. W. J. Roesener,** to the technical sales department of Atomics International.

Mr. Robert Kleiner has been appointed contracts manager of Isotopes Inc., of New Jersey.

Mr. Irwin Stelzer, as sales manager for Alloys Unlimited Chemicals, of Long Island.

Dr. John Ross, one-time with the U.S. AEC Amis Laboratory, as manager of research and development for Metals and Controls, a division of Texas Instruments.

Retirement

Mr. Herbert L. Weinberg, resident manager of the SM-1 at Fort Belvoir.

Honours and Awards

Lord Nelson of Stafford, chairman of English Electric, has been elected an honorary member of the Institution of Electrical Engineers, in recognition of his contribution to the development of electrical science and engineering.

Professor Vasily Emelyanov, chairman of the U.S.S.R. State Committee for Atomic Energy, has been awarded the Order of Lenin on his 60th birthday, in recognition of his services to the development of Soviet nuclear science and technology.

Dr. E. E. Anderson.

Dr. W. J. Stromquist.

Lord Nelson of Stafford.

Prof. V. Emelyanov.

Industrial Notes

Denco Miller, the refrigeration engineering specialists, of Hereford, are supplying three automatic low dew-point dehumidifaction units for use in maintaining clean conditions during the erection and tubing out of the S.R.U.s at Trawsfynydd. They are of different design to the dehumidification plants supplied for use at Berkeley in that they are based on a direct expansion method of operation instead of a glycol system, resulting in a more compact readily transportable unit.

Ether, of Erdington, Birmingham, have been awarded a £12 000 contract for the supply of solenoid valves for use in the R3 project, Sweden.

Hayward Tyler and Co. have been awarded a contract from Babcock and Wilcox for the supply of 16 L.P. and 16 H.P. glandless motor pump units for water circulation in the Sizewell S.R.U.s Value of the contract is about £100 000.

" The Nuclear Power Group " is the title of a 16-minute film about the joint activities of AEI-John Thompson Nuclear Energy and Nuclear Power Plant. It was produced for the group by Films of Today, an associate company of the Film Producers' Guild.

George Kent have formed an Italian company — Kent-Tieghi S.p.A. — which has acquired the complete assets and goodwill of Tieghi, the instrument manufacturers of Milan and Lenno.

I.C.T. (Engineering) is being formed by International Computers and Tabulators, with 10% participation by GEC, for the purpose of assuming responsibilities now undertaken by I.C.T.'s research and design division and the GEC computer development department at Coventry. On the formation of the new company I.C.T. will take over the majority interest in Computer Developments, the company formed by I.C.T. and GEC in 1956 on an equal participation basis.

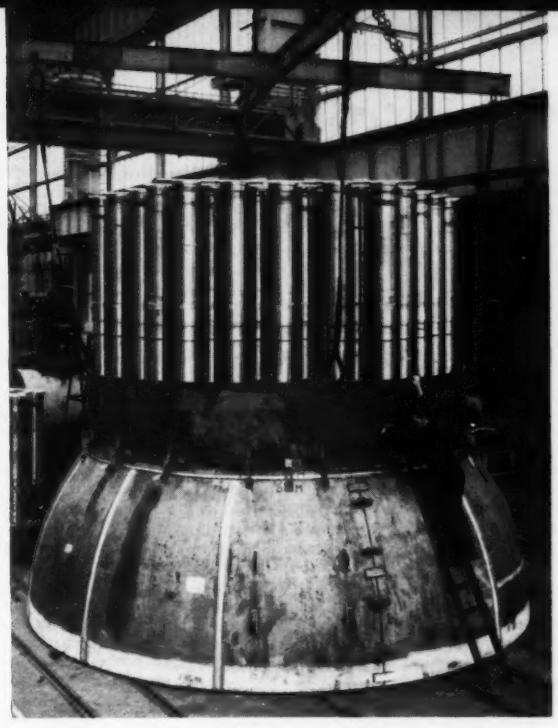
Application forms for the 1961-62 postgraduate course in nuclear technology arranged by the Department of Chemical Engineering and Chemical Technology, **Imperial College,** are now ready.

The Royal Society of Health has opened an exhibition centre at its headquarters in Buckingham Palace Road, London, S.W.1, to display current practice in all branches of public health. One section is devoted to radiation problems.

Head Wrightson Processes have been elected to membership of the Cooling Tower Institute. They are the first British manufacturers to be accepted into this American body.

Nearly 150 exhibits, the products of 100 different electronic equipment manufacturers, were shown at the week-long exhibition organized by **Mullard** in London.

Controls Company of America have formed a British subsidiary. Headquarters are at Woking, Surrey, where assembly operations have already started.



The top dome of the Hero reactor vessel assembled at the Stockton-on-Tees works of Ashmore, Benson, Pease and Co., prior to its dispatch to Windscale.

Stanton and Staveley Sales has been formed to handle sales for the Stanton Ironworks Company, the Staveley Iron and Chemical Company, and the Sheepbridge Company. It will come into operation on July 1.

L. A. Mitchell, of Manchester, have announced that their range of chemical stoneware acid pumps are to be manufactured by Mitchell Craig Pumps (formerly known as Craig Pumps) of Glasgow. New and improved additions to the existing product range will be known as Mitchell Craig pumps.

British Oxygen have just put into operation at Morden, Surrey, a new plant for the production of liquid hydrogen and liquid helium.

IBM United Kingdom are opening during June a computing centre at 58 Newman Street, London, W.1, which will be equipped with IBM 7090 and 1401 data processing systems. These will be available to industrial and commercial users. At present the only other 7090 in use in Europe is with the AEA.

Indatom, of Paris, have been selected by the CEA and EDF as industrial architect for EL-4, to be built near Morlaix, Brittany. They have also been appointed industrial architect for the new swimming pool reactor, Siloe, to be installed at the CEA centre, Grenoble. Under another recently awarded contract, Indatom are to prepare, in collaboration with Belgonucleaire and Siemens, a preliminary design for Euratom's Essor project (see " World Digest ").

Construction of **Tracerlab's** new manufacturing facilities at Mechlen, Belgium, has started. The plant will be occupied by Tracerlab's newly acquired subsidiary, formerly the Physique Industrielle.

Mallinckrodt Nuclear Corporation are supplying AVR of Dusseldorf, Germany, with 325·6 lb of 20% enriched uranium for the 15 MW(e) pebble bed reactor under construction at Jülich. The fuel, which is being made available under the terms of a bilateral agreement between the U.S. and Germany, will be processed by Nukem.

Oak Ridge National Laboratory has reduced the price of technetium-99 from between $1 600 and $2 800/g to $100/g, with a minimum charge of $10/0·1g.

Nuclear Development Associates, of Hathras, India, are offering their services as general consultants to British and European companies interested in building nuclear power plant in India. They announce that they will provide advice on local costing methods, sub-contractors and sources of personnel and materials.

High Voltage Engineering are supplying a three-stage 17·5 MeV Tandem Van de Graaff to Texas University, together with a 4MeV accelerator. The equipment, to cost over $1·8 million, will be housed in the university's proposed $4 million research centre.

The Davison Chemical Division of **W. R. Grace and Co.,** New York, are to undertake the purification and processing of U^{233} for the AI Advanced Epithermal Thorium Reactor project.

The Canadian Nuclear Association has acquired offices at 19 Richmond Street West, Toronto 1, Ontario. Telephone number is Empire 6-4434.

Livingston Laboratories are opening new premises at 31 Camden Road, London, N.W.1, on April 4. The telephone number is GULliver 8501.

Almin have transferred their administrative headquarters to Kynoch Works, P.O. Box 216, Witton, Birmingham, 6. Telephone number is Birchfields 6171.

The Telegraphic address of the **High Voltage Servicing Company,** Chorley Wood, Herts, is " Megavolt, Rickmansworth," not Magavolt, as published in the 1961 " Nuclear Engineering " Buyers' Guide.

We apologize for this error as also for the incorrect postal and telegraphic address and telephone exchange given for **TNPG.** These should all have read Knutsford, not Knutsworth. TNPG is responsible for the construction of Berkeley, Bradwell and Dungeness stations in the U.K. and in Italy, in association with AGIP Nucleare, of Latina.

Technical Papers and Publications

The Institution of Mechanical Engineers

Pressure Vessels for Gas Cooled Graphite Moderated Reactors. By M. J. Noone, M.I.Mech.E., and R. F. Bishop, M.A., A.M.I.Mech.E.

Emphasizing the paramount need for safety, the authors, who are, respectively, director and manager of operations and manager of the engineering division of Whessoe, Ltd., divided their paper into three parts, covering design, materials and construction. The subject of design was itself sub-divided into three sections, covering general stress levels, stresses around openings and stresses in the regions of the supports.

Considering general stress levels, the designs of several pressure vessels were analysed (Table 1) using the appropriate B.S. 1500 current at the time. The first three stations operate at elevated temperature, and a basic stress of 12 000 lb/in² was chosen; later stations were designed so that the shell did not exceed 342°C (650°F). In spite of the apparent equality of stress levels, there had been a continual change in the actual working stresses, as can be seen from the last columns of the table.

These changes in the actual membrane stresses follow modifications of design concept or code requirements. Bradwell, for example, was designed to the 1949 edition of B.S. 1500 and used a shape factor, later stations used the 1958 edition and dispensed with a shape factor. Bradwell and Latina also allowed for thermal stresses caused by the temperature gradient through the shell and differential nuclear heating; this practice has been discontinued. For later designs, such as Trawsfynydd and Dungeness, the membrane self-weight stresses are not deducted or, if deducted, a joint factor of 0·95 has been permitted. These self-weight stresses would be of the order of 700 lb/in².

Gas Pressures

From the general reactor design point of view, there seemed little point in increasing gas pressures above 300 psi with existing forms of canning; future forms might enable higher pressures to give better heat ratings. The saving in blower power from using a higher pressure would give a progressively decreasing return for very high pressures.

Discussing the expectations of pressure increase in the vessel itself, the paper pointed out that future core sizes for the AGR or HTGC would be much smaller, but the relative volume of reflector and shielding would increase. The opinion was stated, however, that in the comparatively near future, the overall dimensions of the pressure containment for civil reactors might be reduced to two-thirds or less of the present sizes.

The maximum shell thickness generally thought suitable was 4½ in, the limitation stemming from three causes; available plate thickness, ability to weld in the field, inspection of the weld. All these factors could, in the opinion of the authors, be overcome. Alloy steels would give an increase in working stress of about 25%.

While it was felt that, by working with lower factors of safety, or by basing designs on yield point, in line with current Continental practice, radical revisions might take place in designs for pressure vessels for normal duty, it was not considered that the change would be acceptable in reactor vessels for some years. The remaining factors, however, would allow pressures up to 600 psi in the reasonably near future.

Stresses Around Openings

Tribute was paid to the valuable work in this field by BWRA, and reference was made to results published by Dr. R. T. Rose in this journal (*Nuclear Engineering*, December, 1958, p. 523). An elegant solution to the problem of providing inside and outside reinforcement around a hole was to combine both types with the vessel wall in one thick plate, applied as an insert, thus doing away with any dangers of differential heating and stress concentration at the outer fillet welds. For spherical vessels, the use of a forged ring, tapered for butt-welding to both shell plates and to the pipe or nozzle, had been generally adopted, and had reduced stress concentration factors considerably.

For a spherical vessel the machining of these forgings did not present any difficulty, since they were pure solids of revolution. For a non-spherical vessel, such as the AGR, considerable skill in manufacture was required. An important requirement, with either form, was that the forgings should meet the mechanical properties as the plate, particularly as regards notch ductility.

Comparisons were made between two methods of supporting a vessel; continuous skirts and supporting columns; a preference was expressed for separate columns which avoided the problems of constraint by the skirt with variations of temperature, and the difficulty of attaching the skirt to the shell and arranging to pick up an internal core-support skirt at the same time. Results were given of experimental work on stub columns attached to spherically-dished plates, both radially and inclined; these agreed very well with the calculated values.

TABLE 1
Membrane stresses of spheres and cylinders at design pressure

Station	Shape	Plate thickness, in	Working pressure, lb/in²	Basic stress used on design, lb/in²	Joint factor used on design	Resultant nominal stress, lb/in²	Actual membrane stress due to pressure, lb/in²	
							Uncorroded	Corroded
Calder	Cyl	2	100	12 000	0·95	11 400	11 100	11 460
Chapelcross ..	Cyl	2	100	12 000	0·95	11 400	11 100	11 460
Bradwell ..	Sph	3	132	12 000	0·95	11 400	8 778	8 965
Berkeley	Cyl	3	125	15 700	0·90	14 130	12 500	12 775
Hunterston ..	Sph	2⅞	150	15 700	0·90	14 130	10 960	11 200
Hinkley Point ..	Sph	3	185	15 700	0·90	14 130	12 310	12 573
Latina	Sph	3⅜	182	15 700	0·90	14 130	10 180	10 370
AGR	Cyl	2⅝	270	15 700	0·90	14 130	11 830	12 100
Trawsfynydd ..	Sph	3¼	240	15 700	0·90	14 130	12 560	12 800
Dungeness ..	Sph	4	268	15 700	0·95	14 900	12 500	12 700

Materials and Construction

Requirements for materials were reviewed. For plates, creep requirements were more stringent than for standard pressure vessel work. If a standpipe 200 in from the centre of the vessel were limited to a maximum movement of ½ in over a 20-year period, the creep rate would be equivalent to 10^{-8} in/in h, whereas 10^{-7} in/in h is considered adequate for standard work. Other important properties were metallurgical stability, corrosion, weldability and notch ductility. The two last were usually the deciding factors; cooling or insulation had reduced the high-temperature requirements.

It was comparatively difficult to obtain the same notch ductility results with forgings, since the forgemaster has not the same advantages of a large reduction from the ingot dimension. Progress had been made, however, and satisfactory Charpy results were tabulated for both 5-6 ft rings and smaller standpipe nozzles for Bradwell and Latina.

In the section on construction, an account was given of the improvement obtainable in notch ductility by controlled hot pressing. New plant installed for the purpose allowed precise temperature control of the plate so that the entire hot-pressing operation took place within a narrow band of temperatures around the normalizing range. This avoided the troubles usually encountered with hit-or-miss methods, when the properties of the plate after hot pressing were completely changed from the as-received condition, requiring subsequent normalizing, with inevitable risk of distortion—which might or might not be completely corrected by subsequent cold pressing.

An interesting item in this section was the top dome for the AGR. This uses the design concept of a considerable thickening of the top dome itself (1¾ in-3¾ in), to provide the major portion of the reinforcement, thus allowing comparatively light nozzles to be used. With 6 in i.d. nozzles, on a 10¾ in triangular lattice, thick nozzles would have required very heavy attachment welds, with adjacent welds very close. This would have been very difficult to weld, even more difficult to inspect, and very susceptible to cracking.

Controlled Fusion Reactions. (The Forty-seventh Thomas Hawksley Lecture.) By Professor P. M. S. Blackett, M.A., F.R.S.

Not much of outstanding novelty or importance has been published on this subject since the 1958 Geneva Conference; such a comment is a rough summary of the introduction to this paper. The Geneva conference might be regarded as the peak of a wave of declassification of information

which commenced in 1956 with a paper read by Kurchatov at Harwell, telling of Russian work in this field. An uncontrolled fusion reaction had been possible since 1953; progress towards the production of a controlled fusion reaction was slow.

The basic principles of the fusion reaction were reviewed, as well as a number of types of approach to the problem, including dynamic and semi-static self-pinched plasma devices, magnetic compression devices and ionic injection into a static magnetic bottle.

All these devices have previously been reviewed, and the author made it clear at the outset that he proposed to confine his paper to a review of the existing state of the art, and to drawing conclusions for future possibilities. It was convenient to envisage future developments in four stages. The first that he visualized might be called a diagnostic reactor; it would give an adequate output of neutrons arising from completely thermalized deuterium ions, and would enable a sensitive diagnosis to be made of the physical conditions of temperature and particle concentration in the plasma. It was essential that neutrons from truly thermalized ions should not be swamped by neutrons of the " wrong sort," i.e., from directly accelerated ions. The energy efficiency of such a device would be about 10^{-6}. Some idea of the difficulty of such a project could be obtained from the fact that the labours of hundreds of scientists over the past ten years had not yet produced—at least as far as published information was concerned—a really adequate diagnostic reactor.

The next step would be a neutron source reactor which gave, say, 10^{16} neutron/s for an input of 1 MW. This would represent an efficiency of about 10^{-2} which would necessitate an improvement of 10^{12} over existing devices—even the two-stage magnetic compression device at Livermore only had an efficiency of about 10^{-14}.

The third step would be the construction of a " non-economic " power reactor, which had an efficiency greater than unity. It was quite impossible to foresee what such a reactor might be like, or how large it might be; advance in basic knowledge of plasma physics might drastically change our ideas of what it might be like—or even prove that it was not possible on any earthly scale.

The fourth step would be the creation of an economic reactor, but all four steps were mere crystal-gazing. If we turned from this to the problem of planning a rational research programme, it would be well to forget all the four steps—except, perhaps, the diagnostic reactor—and concentrate on learning a great deal more about the fundamental physics of plasmas. The attempt to travel a long way in one step, by large machines like ZETA, Stellerator, Columbus, OGRA, etc., had failed. It had been a worth-while exercise — the corresponding gamble on the first fission reactor had succeeded—but what was now necessary was several years' work on a relatively modest scale. It was difficult to decide on what scale equipment should be—working too small might make scaling-up difficult, working too large meant slower experimentation and fewer lines of attack for the same amount of money. Experience had shown the value of the moderate-sized apparatus (say £50,000 capital cost) with a team of about six. It was well to remember something of which Dr. Gabor had recently reminded us; how little in the field of plasma physics had been predicted, and how much discovered experimentally, and Mr. Brobeck's dictum, that in comparing proposals neither of which would work, the simpler is to be preferred.

Symposium on User Experience of Large-scale Industrial Vacuum Plant. March 1-2.

Fourteen papers were presented at this symposium, ranging in subject from the use of vacuum plant in nuclear fuel processing to the freeze drying of foodstuffs and human plasma. The meeting, which was sponsored by the Joint British Committee for Vacuum Science and Technology, was attended by 270 delegates, representing both maker and user interests.

One of the best received papers was on the **Applications of Electron Bombardment Heating in Metallurgy,** by N. F. Eaton, of AEI (Manchester), and D. B. Gasson and F. O. Jones, of AEI, Aldermaston. The most advanced of the various electron beam devices they briefly described is capable of heating efficiently areas from 1 to 100 mm² and the ease and accuracy with which the beam can be adjusted in direction and power make it one of the more versatile types of heat sources available. Most of the paper was devoted to descriptions of the techniques developed for zone refining, silicon crystal production, and welding (this aspect was covered more fully by Dr. Eaton in *Nuclear Engineering*, January, 1960, pp. 19-22).

The advantages of electron beam furnaces over high frequency induction and consumable electrode arc furnaces for vacuum melting and casting of metals were pointed out. Material to be melted does not have to be made up into electrodes and because the width, depth and temperature of the melting pool can be controlled to a greater degree than that possible with an arc there is less likelihood of re-entrapment of dross, minimum trouble from porosity and improved control of solidification.

One of the main difficulties with electron beam melting is the problem of pressure rise due to the volatilization of impurities, or of the metal itself, which can lead to electrical discharge breakdown. To overcome this AEI are developing a 100 kW furnace in which the various electron guns used are isolated from the melt chamber in a separately evacuated system. The apertures between the melt and gun chambers will be large enough for a beam to pass through but small enough to attain the required pressure differential.

Incidentally, little reference was made to the radiation shielding necessary when voltages over the 20 to 30 kV range are used, an important consideration.

Consumable electrode arc furnaces were covered in the paper, **Vacuum Equipment for Consumable Electrode Melting of Reactive Metals,** by G. W. Turner and K. Deutsch, of ICI. They described their experience with three generations of such furnaces used for processing titanium and zirconium—the last generation capable of dealing with up to 2 ton ingots. In their conclusion they are confident that even larger furnaces operated on a production basis are possible. Referring to the possible use of vacuum furnaces for lower priced materials they point out that modifications such as to the pumping system will be necessary to make them cheaper.

In his paper on **Experience Obtained by Springfields on the Application of Vacuum to Fuel Element Production Processes,** Mr. A. E. Williams, AEA research manager, referred to the problem of beryllium evaporation encountered in using vacuum melting techniques which results in contaminated pump oil, equipment and gaseous effluent. This effluent can contain beryllium fumes and it has to be treated. Connecting the exhaust system to the ventilation system of the building is not satisfactory on account of the appreciable quantities of volatilized oil, which presents a potential fire hazard and can seriously impair the filters which are fitted to clean the air before it is pumped to the atmosphere. Individual filters and demisters on the pump lines have been found to give little benefit under these conditions. A method now being considered is to pipe the effluent in 2 in bore ducting to a single oil removal system.

BNL 628 (T-193). Status of Direct Conversion Programs in the United States, with Special Emphasis on Civilian Nuclear Power. (Edited Version) William A. Robba. Brookhaven National Laboratory. (Office of Technical Services, Department of Commerce, Washington 25, D.C. $0.50.)

This report surveys the status (at May, 1960) of developments in the field of direct conversion, including thermoelectric, thermionic, MHD (magneto-hydrodynamic) methods as well as fuel cells, considered in the light of possible applications to civilian nuclear power plants. The survey was carried out for the Division of Reactor Development of the U.S.AEC, and covered a number of companies known to be working in this field; a number of techniques were not investigated in detail either because they were fundamentally inefficient (below 3%) or not developed to a point of practicality, or because they were intrinsically associated with a non-nuclear energy source (e.g., solar energy).

Thermoelectric and fuel cell devices are said to be in the most advanced stage of development, the SNAP programme being instanced as an example of isotope-thermoelectric work. Least developed is said to be the MHD, mainly due to the extremely high temperatures and large sizes required for efficient operation. Although two companies (AVCO and Westinghouse) were said to have experimental machines operating with arc plasma and oil firing respectively, in the 10kW range, output was obtainable for a few seconds only at a time.

The general trend of the report would seem to indicate that the driving force behind current programmes came from military or space projects. A possible exception was the MHD on which there might be large-scale developments within the next decade.

MEETINGS

March 29.—The British Institution of Radio Engineers (at 9 Bedford Square, London, W.C.1, 3 p.m.). A symposium of six papers, **Electronic Instrumentation for Nuclear Power Stations.**

April 12. The Institution of Chemical Engineers (Midlands Branch, at the Chemical Engineering Department, The University, Edgbaston, Birmingham, 15). **Symposium on Materials of Construction,** including papers on **Fabrication and Properties of Some of the Newer Constructional Metals** (Dr. N. P. Inglis) and **Recent Developments in Wrought Corrosion Resistant Nickel-base Alloys** (E. Warde).

April 13.—The Institute of Physics and the Physical Society (Liverpool and North Wales Branch, at The University, Liverpool, 7 p.m.). **Experiments on Rapid Magnetic Compression of a Plasma.** Dr. G. B. F. Niblett.

April 17-18.—The Institute of Physics and the Physical Society (in conjunction with the B.N.E.C. at The University, Edgbaston, Birmingham, 15). **Conference on Nuclear Energy.**

April 21.—The Institute of Physics and the Physical Society (South Wales Branch, at University College, Aberystwyth, 5.15 p.m.). **European Co-operation in Nuclear Research.** Dr. G. R. Evans.

April 24.—The Institution of Chemical Engineers (in conjunction with the B.N.E.C. at The Geological Society, Burlington House, London, W.1, 5.30). **Fluid-fuel Nuclear Reactors.** A. M. Weinberg.

Patents Reviewed

These abstracts have been made from British Patent Specifications, complete copies of which can be obtained from the Patent Office, 25 Southampton Street, London, W.C.2, at 3s. 6d. each (including postage).

B.P. 843,871. Gas-cooled nuclear reactors. E. Long. To: U.K. Atomic Energy Authority.

A control means for emergency shut-down of a reactor is obtained by injecting into the coolant circuit an inert gas with a high absorption cross-section, to reduce the reactivity. A carbon-dioxide-cooled, graphite moderated reactor may be shut down by the addition of argon, xenon, or nitrogen to the carbon dioxide. These gases will also assist in suppressing any fires. They may later be removed by purging the system with pure coolant.

B.P. 843,963. Gas discharge apparatus. P. C. Thonemann. To: U.K. Atomic Energy Authority.

A thick-walled aluminium torus with a series of transverse slots in its inner wall sealed with insulating material or bridged by thin metal sheet (0.02 in stainless steel or $\frac{1}{16}$ in aluminium) so that the torus remains vacuum-tight. The electrical resistance of the inner wall of the torus is thus increased so that the eddy currents induced therein are reduced.

B.P. 843,941. Remote control device. To: Commissariat à l'Energie Atomique (France).

The device is composed of two frames, one to be actuated by the operator, the other carrying the means for performing the desired manipulations. Three separate mechanisms connect points on the one frame to corresponding points on the other, so that identical displacements are produced. The mechanisms may be assemblies of rods, tubes or the like eliminating most of the gears, pulleys and cables necessary in the known control devices. The device may be balanced so that the operator has a "feel" of the body to be handled.

B.P. 844,167. Heat exchange surfaces. L. A. Husain. To: U.K. Atomic Energy Authority.

A sheath for nuclear fuel in the form of a corrosion and high-temperature resistant tube with a filament wound around the tube which has low neutron-absorbent properties. The tube and filament may be graphite or the tube stainless steel and the wire zirconium.

B.P. 844,211. Nuclear reactor. P. P. Guneratine. To: U.K. Atomic Energy Authority.

The fuel member enclosed in a protective sheath contains a thermocouple hot junction. A cable is inserted during fabrication, passing through the sheath and sealed thereto so that drilling of the uranium is avoided.

B.P. 844,291. Thermonuclear reactor. To: U.S. Atomic Energy Commission (U.S.A.).

Refers to the control of stellarators (an endless tube in which ionized gas is confined by a very strong externally applied magnetic field) as, e.g., described in U.S. Patent 2,910,414. The arrangement of an axial magnetic field inside the reaction tube, together with the simultaneous application of a multipolar magnetic field transverse to the axis of the tube, improves the effectiveness of the confining field.

B.P. 844,401. Pressure vessel assemblies. J. J. Griffith. To: U.K. Atomic Energy Authority.

The support of the vessel is a pressure chamber extending vertically downwards from an opening in the base of the vessel and open to the vessel. The core support grid within the vessel is carried by the chamber and a coolant inlet duct is connected into the chamber. Thus the region where the pressure vessel joins the support chamber can be maintained at the uniform temperature of the coolant entering the duct.

B.P. 844,408. Steam raising plant. J. M. Mitchell. To: General Electric Co., Ltd.

A dual-pressure steam raising unit where the coolant is circulated by a steam turbine supplied with high pressure steam from the unit, the steam being discharged at a pressure corresponding to that of the low-pressure steam raised within the unit.

B.P. 844,475. Nuclear reactor. To: Siemens Schuckertwerke A.G. (Germany).

The ability of a moderator to slow down neutrons depends to a large extent upon its density and this specification describes the cooling arrangement for a moderator liquid to obtain highest density. The cooling system comprises a main circuit communicating via a heat exchanger with cooling channels in the reactor core and a duct branching off at a point after the heat exchanger communicating via a cooling device with a moderator space in the reactor. In operation only that fraction of the cooling medium required for moderating purposes passes this duct.

B.P. 844,605. Nuclear reactors. P. R. J. French. To: British Thomson-Houston Co., Ltd.

The fuel element is a tubular member with radial projecting fins integral with or rigidly secured to the tube; both parts, tube and fins, are of fissile material.

B.P. 844,711. Nuclear reactor. To: U.S. Atomic Energy Commission (U.S.A.).

A power-producing reactor in which the moderator is a fluid compound of deuterium and the fissile fuel is cooled by liquid metal. A (zirconium) conduit extends through the fluid moderator container and a fuel element assembly (a number of spaced fuel rods of enriched uranium) is arranged in the conduit. A liquid metal coolant (sodium) circulates through the conduit, flowing downwards past the fuel rods. No pressure vessel is required.

B.P. 844,757. Method of increasing the rate of heat transfer between hot surfaces and a liquid in contact therewith. K. H. Steigerwald (Germany).

The hot surface is heated to such temperature that a stable film of vapour is formed which separates the liquid from the heated surface. Heat transfer is obtained by a voltage applied between liquid and surface, of such magnitude as to produce an electric discharge through the vapour film. An a.c. voltage or a pulsating d.c. voltage is especially advantageous. To increase the effect of the discharges a magnetic field may be produced in and/or near the region of the discharge zone.

B.P. 844,781. Method of resisting radiation damage to organic fluids and compositions therefor. To: U.S. Atomic Energy Commission (U.S.A.).

It has been discovered that the lower alkyd styrene polymers effectively thicken various base oils and impart to the mixture nuclear radiation resistance. A few per cent. of these oil-soluble alkyd styrene polymers are sufficient for this purpose.

B.P. 844,833. Nuclear reactors fuel preparation. To: U.S. Atomic Energy Commission (U.S.A.).

Preparation of an easily dispersed stable suspension of uranium dioxide in bismuth by heating and agitating in which bismuth oxide is added to bismuth and uranium in an amount somewhat less than that theoretically required to oxidize the uranium to uranium dioxide.

B.P. 844,884. Nuclear reactor. W. G. E. Wood, B. P. Thomas. To: AEI-John Thompson Nuclear Energy Co., Ltd.

A gas-cooled nuclear reactor with graphite core in which the blocks are arranged in vertical stacks and horizontal layers with a central compensating zone for Wigner growth and an annular uncompensated zone. The horizontal dimension of the uncompensated zone is a maximum at the top of the core and is reduced progressively, or in steps, to a position about midway down the reactor where it ceases. This minimizes distortion of fuel channels and control rod channels.

B.P. 844,980. Method of producing dense uranium oxide bodies. To: U.S. Atomic Energy Commission (U.S.A.).

Sintering in a steam atmosphere at 1 300° to 1 400°C uranium oxide grain of an oxygen-uranium atomic ratio less than 2.02 and a particle size of less than 1 micron.

B.P. 845,207. Control of nuclear reactors. L. C. Ludbrook, P. R. J. French. To: British Thomson-Houston Co., Ltd.

Vertical control rods are arranged in groups forming concentric circular loops, all the rods in one group being moved simultaneously. The groups are raised in succession, the outermost group first, and lowered with the innermost group first. In this way, a linear relationship is given between the reactivity and the positioning of the control rods.

B.P. 845,305. Pressure vessels for nuclear reactors. S. Hackney. To: U.K. Atomic Energy Authority.

Refers to the support structure for a pressure vessel in a ship. The vessel is supported at its lower end by a perforated conical skirt resting on a support structure in the ship. This support structure also carries the side and base shielding. A straight skirt extends from the upper region of the vessel free to move axially and carrying the top shielding through which charge tubes pass, coolant ducts and control rod tubes being provided in the wall of the pressure vessel.

Processes and Equipment

For further information on any item please enter the relevant number on the Reader Service Card enclosed with this issue and forward the card to the address given.

Versatile Remote Handling Unit

Adaptability to a wide range of tasks under "hot" conditions is a feature of the Mobot Mark II, which has been developed by the Hughes Aircraft Company, Los Angeles, from an earlier model in service at the Sandia Corporation's radiation laboratories in Albuquerque, New Mexico.

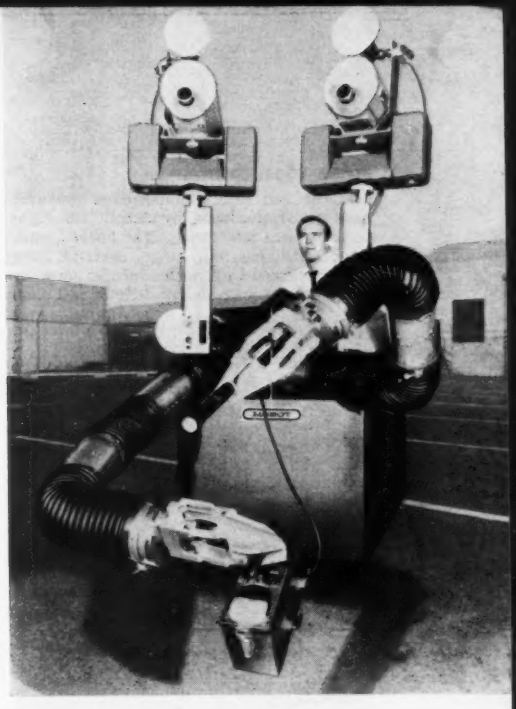
The Mark II Mobot has three joints in each arm, corresponding to shoulder, elbow and wrist, each being double-jointed, and operated by electrical actuators which give it 10 different movements in each arm. The arms are mounted on a desk-like steel cabinet on wheels and, in conjunction with two swivel-mounted television cameras, form a completely mobile unit, independently controlled from a remote console. From this, in addition to controlling the arm movements and steering of the unit, it is possible to adjust the focus, pan and tilt of the cameras, as well as the movements of their associated spotlights.

Delicacy of touch, which is sometimes most necessary on this type of gear, is obtained by soft inflated pads on the hands, and it is claimed that it is perfectly possible to replace an ordinary electric lamp without damage. A further refinement is the provision of microphones built into the wrists, thus considerably adding to the natural "feel" of the operation.

Another development well under way is the use of a tape "memory" to enable complex routine operations to be performed automatically.

(Hughes International (U.K.), Ltd., Glenrothes, Fife.)

1070



The Mobot Mk. II, holding a Geiger counter and detector head.

New Heating Tapes

Main feature of Hotfoil heating tapes, recently introduced, is the use of flat foil conductors, instead of round wires, thus giving a considerably increased area of contact. Since a round wire, in theory, gives only a line contact. The improved heat transfer and reduced temperature gradient thus enables the heating element to be run at a lower temperature for the same heat transfer, and therefore eases insulation problems. In a 1-in wide tape, for example, the net heating surface is no less than $\frac{1}{4}$ in.

The foil strips, which are slightly crimped to allow for stretching, are individually insulated with Melinex, a high-temperature polyester material, and are then moulded into a sheath of the same material, which provides automatic spacing of the conductors in a damp-proof tape. This, known as Type A, is suitable for applications up to 110°C, and is manufactured in lengths from 12 to 100 ft, with loading from 130 W to 3 kW. Type E is similar in characteristics, but has additional woven glass covering.

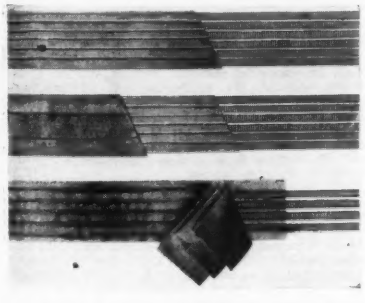
A further variety, for temperatures up to 450°C, is insulated with three layers of woven glass, and is suitable for loading up to 15 W/in²; standard lengths range from 6 to 70 ft.

All standard lengths are designed for 230/250 V, but other voltages can be supplied. Standard endings are in silicone elastomer for types A and E; Type G have glass-insulated leads and anchor rings.

Tape can be applied either as straight trace lines or spiralled around the pipe, according to the loading required. The material is also made up into heating mantles for vessels, and a further application is the direct moulding of the material into the walls and bases of moulded glass-fibre containers. A full range of thermostats and energy regulators is available.

(The Midland Electric Installation Co., Ltd., Upper Villiers Street, Wolverhampton, Staffs.)

1071



Hotfoil heating tapes. Top to bottom; Types A, E, and G.

Metallurgical Specimen Service

Cutting a test specimen from a plate may seem a simple operation, but with the number of specimens nowadays necessary, the problem of producing perhaps several hundreds—or even thousands—accurately machined and identified, requires almost an organization on its own. To meet this need, a service is offered which will produce test specimens accurately machined and identified as required. All specimens are subject to 100% inspection—in the case of Charpy impact specimens, notch profile is checked by projection methods—and loss of identity is obviated by a coded cutting layout.

To avoid any possibility of contamination by non-ferrous impurities—which, in the case of specimens intended for irradiation, might prove extremely troublesome—a special production line of saws, shapers, millers and grinders has been laid down in a new factory devoted to this work.

(Weston Electric Units, Ltd., Foulridge, Colne, Lancs.)

1072

Digital Volt-ohm Meter

Designed for measuring voltages from 1 mV to 1·1 kV, and resistances to 1·1 megohms, a new Venner transistorized instrument displays the results in digital form via four in-line projection indicators, automatic sign indication being provided. At the same time, the DVOM will record via a printer or reperforator and can be included in any data logging system, as well as being used as a single instrument.

Venner digital volt-ohm meter.

(Venner Electronics, Ltd., Kingston Bypass, New Malden, Surrey.)

1073

Area Monitors

Linear and logarithmic gamma monitors have been introduced by A.E.I., for high-accuracy area monitoring. The linear model, type G.M.1, has four ranges covering from 0-125 mr/h to 0-1 r/h, with a relative accuracy of ±3% and a seven-day drift of less than 2%. The G.M.2 has a measuring range extending from 0.1 mr/h to 10 mr/h, calibrated logarithmically over 5 decades, with approximately the same accuracy and stability; i.e., ±3% and 2%/7 days.

Type G.M.1 area monitor; front view.

Both types have a large ionization chamber filled with argon and air, to obtain maximum flatness of gamma energy response, and an electrometer valve as a cathode follower. Other features are the use of transistors, except for the input electrometer stage, and an instrument failure system which operates a visual or audible warning differing from the radiation alarm. The ionization chamber may be mounted remotely, if desired. The instruments are mounted in splash-proof aluminium cases, with setting controls inaccessibly located, to prevent tampering, or accidental alteration.

(Associated Electrical Industries, Ltd., Instrumentation Division, Harlow, Essex.)

1074

New Ultrasonic Detector

The new Sonatest type TE/2 flaw detector is said to be robust enough for site work and of a degree of accuracy suitable for laboratory work. The ability to operate up to 15 Mc/s without loss in sensitivity makes it possible to locate micro-cracking and inclusions in welds and forgings which could not be detected at lower frequencies. It is also possible to measure very thin specimens with these high frequencies, and it is stated that thickness measurements on a 1-in diameter tube, of wall thickness only 0.025 in, can be made by sliding a probe through the bore. A wide range of robust probes suitable for operation up to 15 Mc/s is available.

The Sonatest TE/2 with typical probes.

The depth range in steel is 0-20 ft, and a vernier gain control is fitted.

The tube is a 5-in, flat-faced type with a very bright blue-green trace, and a non-parallax graticule with an ambient light filter for outdoor work. The instrument may be purchased outright, or obtained on contract hire, the rental including insurance; modifications to new developments, and 24-hour replacement service.

(Sonatest, Ltd., 15 Great James Street, London, W.C.1.)

1075

Flow Indicator

A new flow indicator, which gives at sight an approximate indication of the proportion of full flow in a pipe, is suitable for operation either horizontally or vertically with flow either upwards or downwards. If desired, a fractional scale may be added. The unit is made in six sizes for pipes from $\frac{3}{4}$ in to $2\frac{1}{2}$ in bore, the overall lengths ranging from $4\frac{1}{2}$ in to 6 in; corresponding overall diameters ranging from $1\frac{13}{16}$ in to 3 in. The body is in bronze and is pressure-tested to 100 psi. Standard B.S.P. threads are used.

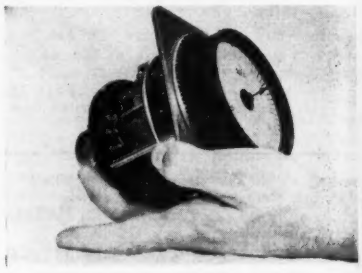
Suba Model 112 vane-type flow indicator.

(Suba Hydraulics, Ltd., Limes Place, Limes Road, Croydon, Surrey.)

1076

New Synchronous Timer

Elimination of the setting knob—setting being by rotating bezel—is one of the features of a new synchronous timer unit, for wall or panel mounting. The time setting is infinitely variable within the range of the instrument, and visual indication of elapsed and unexpired time is given. Operation is by a solenoid clutch, the timer resetting when the clutch is de-energized. Two models are manufactured, either switching during timing cycle, or at the end of timing cycle. Voltages available include 110 V and 200/240 V 50 60 c/s, and 400/440 V 50 c/s, and the switching capacity is 5 A at 240 V or 0.5 A at 440 V. Time ranges are 12, 30, 60, 120 and 180 sec; 6, 10, 20, 30, 60, 120 and 180 min; 6, 12 and 24 hours.



Elremco "Star" synchronous timer.

(Electrical Remote Control Co., Ltd., Bush Fair, Harlow, Essex.)

1077

BRIEFLY . . .

Scientific Furnishings, Ltd., Poynton, Cheshire, are handling the new Electrosensor voltmeter developed in the U.S. by Halex Inc. Claimed to have a sensitivity two orders of magnitude better than commercial instruments available, it is capable of measuring a flow of only 60 electrons/s, equivalent to 10^{-16} amps. Effective input impedance is above 10^{11} ohms. **B231**

Two new smaller sizes have been added to the "Thermocoax" range of miniature thermocouple wires marketed by **Research and Control Instruments, Ltd.,** Instrument House, 207 King's Cross Road, London, W.C.1. Of chromel-alumel, with stainless steel sheath the new wires have overall diameters of 0.34 mm and 0.25 mm. They are available in limited lengths up to 6 metres. **B232**

Vitro Corporation of America, West Orange Laboratory, 200 Pleasant Valley Way, West Orange, New Jersey, announces that it is now able to supply uranium monocarbide, in laboratory quantities, as granules or spheres from 200 mesh to $^{5}/_{16}$ in diameter. Vitro is also developing processes for polycarbide production, such as UC CbC; UC ZrC; UC_2ThC_2, also boron and silicon carbides. **B233**

Pressures up to 100 000 psi for hydraulic test purposes can be obtained from a new "Airhydropump" developed by **Charles S. Madan and Co., Ltd.,** Vortex Works, Altrincham, Cheshire. Intended for operating from a conventional compressed air supply, this model has been developed from a previous type, operating at 55 000 psi, of which many have been in continuous use for several years. The new pump has an output of rather more than 6 in³/min at 10 000 psi, falling to about 2 in³/min at 90 000 psi, and has actually been tested at 132 000 psi. A range of valves and pipe fittings is available. **B234**

Tretol, Ltd., Tretol House, The Hyde, Hendon, London, N.W.9, announce the production of "Epiflor," a new flooring composition, said to have exceptional resistance to oils, acids, and many chemicals, and resists hard wear by foot traffic and trucks. **B235**

A new range of inks and powders for magnetic crack detection is announced by **Southern Tools, Ltd.,** 22 Upper Mulgrave Road, Cheam, Surrey. Three powders are available in black, grey, and copper-red, the last being only a little less sensitive than the other two, and giving good contrast. The inks, a black/grey and a fluorescent, are supplied in concentrate form for dilution with water. **B236**

A microminiature incandescent lamp, the "Mite-T-Lite," produced by the Special Products Division of **Thorn Electrical Industries, Ltd.,** Thorn House, Upper St. Martin's Lane, London, W.C.2, is only 0.055 in in diameter, and 0.175 in long. Rated at 1-1.5 V, the lamp takes only 30 mA at 1.3 V, thus permitting direct operation from a transistor. **B237**

Dowty Seals, Ltd., Aschurch, Glos., have produced a new range of seal rings in a silicone compound (S.E.M.895) possessing improved properties of resistance to temperature, radiation and compression set. An extensive test programme, including high-energy electron radiation, has enabled the seals to be offered in O-ring form for temperatures up to 150°C, and in rectangular sections for 175°C, or up to 250°C for short periods. Developments under way include a metal seal with flexible lips for operation at 300°C, and 600°C is envisaged in the near future **B238**

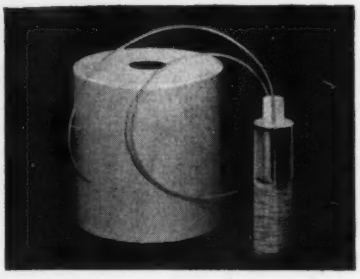
The teaching of metallurgy in educational establishments should be backed up by examination of micro-specimens of known composition. To this end, **Metallurgical Services,** Reliant Works, Betchworth, Surrey, are producing sets of annotated specimens of various alloys, with full details of their structure, method of preparation and chemical analysis. There are, at the moment, 15 sets available, each set containing from 6 to 18 specimens, the sets ranging from sand-cast grey and white cast irons to complex brasses. **B239**

Lighting fittings suitable for closed-circuit television illumination in difficult surroundings are announced by **P. W. Allen and Co.,** 253 Liverpool Road, London, N.1. One standard dust-tight and waterproof housing, spun from 16g steel, with $\frac{1}{4}$ in plate glass window held between aluminium rings, may take either spotlight or floodlight lamps. Mounting is by means of a clamp on a 2 in tubular column, the lamp being adjustable in all directions. **B240**

Flow Monitor

The NE 813 detector has been developed for the continuous monitoring of gamma activity in effluents from ion exchange columns, for medical and biochemical studies and for isotope monitoring in aqueous or organic media.

The detector consists of an 8 ft length of PTFE tubing, 1·3 mm i.d., coiled on a 1¼ in



The NE 813 gamma monitor.

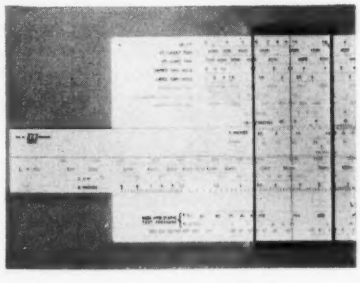
rod of plastics phosphor, type NE 102, this being surrounded in a well-type phosphor unit 5 in diameter x 5 in high. The unit can be mounted on any 5 in dia. photomultiplier, using silicone fluid as a coupling medium. The PTFE tubing is chemically inert, easily cleaned, and insoluble in all solvents at normal temperatures. Special diameters of tubing can be supplied, if required.

(Nuclear Enterprises (G.B.), Ltd., Bankhead Medway, Edinburgh, 11.)

1078

Pipe Calculator

Those engaged in pipework calculations will be interested in a new slide rule designed for that purpose by Mr. I. Alexander of Intercontinental Enterprises. Examples of



The Blundell pipe calculator.

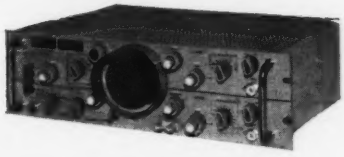
problems solved in a matter of seconds are weights of pipes in different materials when the diameter and wall thicknesses are known, bursting or working pressures, relative carrying capacities, price calculations. Calibration is in British, U.S. and metric units.

(Blundell Rules, Ltd., Regulus Works, Lynch Lane, Weymouth, Dorset.)

1079

Double-beam Oscilloscope

A new twin-beam oscilloscope has been developed, suitable for rack mounting, the dimensions being 19 in wide, 5¼ in high and 14½ in overall depth (13 in behind panel). Known as the CD 1016, the instrument has two Y amplifiers, covering the range d.c.–5 Mc/s, with a rise time of 70 mμs, and nine calibrated sensitivity ranges, switched in 1-2-5 sequence from 100 mV/cm to 50 V/cm; an additional fine control gives a continuous range up to



Solartron CD 1016 twin-beam oscilloscope.

100 V/cm. The time base is adjustable from 1 cm/μs to 2 cm/μs, or a maximum of 5 cm/μs using X expansion.

(Solartron Laboratory Instruments Ltd., Cox Lane, Chessington, Surrey.)

1080

Portable Vacuum Gauge

A new portable vacuum manometer, the N.E.L., is designed to eliminate errors arising from leakage of air into the closed limb, by the use of a bulb at the top of the closed

The N.E.L. portable manometer.

limb, for the expansion of entrapped gas or air, and an identical bulb at the foot of the open limb; a short length of capillary tube is used to connect the two limbs. The range of the instrument is 0-300 mmHg.

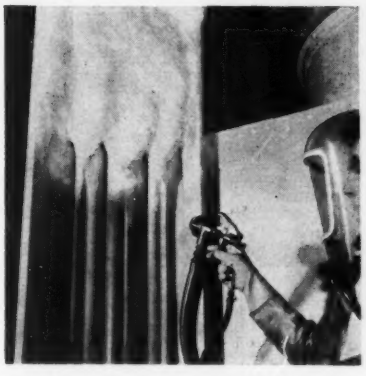
The error at 300 mmHg, as compared with a conventional design with the same volume of entrapped gas is said to be 0·33 mm, compared with 17 mm for the conventional design.

(NGN Electrical Ltd., Accrington, Lancs.)

1081

Foam Insulation

Rigid polyurethane foam is rapidly sprayed in position, for thermal insulation of roofs, air ducts, pipes, etc., and for mechanical protection. The composition is a product of



"Foam-in-place" spray equipment applying pipe insulation.

the Baxenden Chemical Co., Ltd., and is Freon-blown; it has a K-factor of 0·11-0·14 Btu/ft² °F h per inch of thickness at 75°F and an average density of about 1·6 lb/ft³; it rapidly hardens without shuttering or battening.

(The Aerograph-DeVilbiss Co., Ltd., 47 Holborn Viaduct, London, E.C.1.)

1082

CATALOGUES

La Compagnie General de Télégraphie Sans Fil have issued a brochure to mark their fiftieth anniversary.

"This is United Steel" is the title of a brochure received from the **United Steel Companies Ltd.,** The Mount, Sheffield, 10.

The 1961 edition of *The Engineer* Buyers' Guide has now appeared, containing some 980 pages of information. The guide section consists of 2 700 classified headings containing more than 3 500 entries. It is available from the offices of *The Engineer* at 28 Essex Street, Strand, London, W.C.2.

The Stainless Steel Fabricators' Association, Chamber of Commerce House, P.O. Box 360, 75 Harborne Road, Edgbaston, Birmingham, 15, has issued a list of members and classified list of products.

From **British Sarozal, Ltd.,** Industrial Sales Division, 22 Berners Street, London, W.1, comes a list of precise measurement equipment, including transducers, amplifiers and recorders.

The services available in their industrial plant department is the subject of a publication from **Thos. W. Ward, Ltd.,** Albion Works, Sheffield. In addition to ducting and pipework, tanks, pressure vessels and large and small fabrications, the services of two subsidiary companies, **Dick's Asbestos and Insulating Co., Ltd.,** and **Anchor Insulating Co., Ltd.,** are included.

A leaflet from the **Westrex Co., Ltd.,** 152 Coles Green Road, London, N.W.2, covers their personal call system.

Bryans Aeroquipment, Ltd., 1 and 5 Willow Lane, Mitcham, Surrey, have sent us particulars of their electric plotting equipment, together with information about their trace interrupter system, which enables graphs to be plotted in various dotted patterns.

"Machining Wiggin High-Nickel Alloys" is the title of a new publication received from **Henry Wiggin and Co., Ltd.,** Wiggin Street, Birmingham, 16.

Contactors and telephone type relays are described in lists received from **Londex, Ltd.,** Anerley Works, 207 Anerley Road, London, S.E.20.

Elcontrol, Ltd., Wilbury Way, Hitchin, Herts, have issued a publication covering liquid level controls and probe fittings.

A new bulletin from the **Brooks Instrument Co. Inc.** of Hatfield, Pennsylvania, describes the "Hi-Pressure" rotameter for pressures up to 5 000 psi.

List DC. 44, published by **Ferranti, Ltd.,** 68-71 Newman Street, London, W.1, describes the Pegasus 2 Computer System.

Shaker hearth furnaces are described in a new publication received from **Efco Furnaces, Ltd.,** Queens Road, Weybridge, Surrey.

EMI Electronics, Ltd., Hayes, Middx, have issued a short form of catalogue of nuclear health equipment.

Two publications from the **Brooke Tool Manufacturing Co., Ltd.,** Warwick Road, Greet, Birmingham, 11, cover the machining of nuclear graphite and special carbide tipped cutters and reamers.

A new leaflet from **Claude Lyons, Ltd.,** Valley Works, Ware Road, Hoddesdon, Herts, covers stabilized d.c. power supplies.

"Metox" miniature oxide resistors are described in a brochure received from **Welwyn Electric, Ltd.,** Bedlington, Northumberland.

Electro-hydraulic remote handling equipment manufactured under licence from CEA is described in leaflets issued by the **Société d'Optique et de Mécanique de Haute Précision,** 125 Boulevard Davout, Paris XX.

The first number of *Sima Review*, published by the **Scientific Instrument Manufacturers' Association, Ltd.,** 20 Queen Anne Street, London, W.1, has appeared. It will take the place of the previous *Sima Bulletin* and will appear twice yearly.

Orbits . . .

THE SUCCESS of the Faraday Lecture, "Transistors and All That" by Mr. L. J. Davies, in its tour around the country, stirs us to repeat once more our suggestion for a similar lecture on nuclear affairs. As we have previously pointed out, two Faraday lectures devoted to this subject have been given (both by Dr. T. E. Allibone) but two lectures in more than ten years is not enough. The only question is . . . Who is to do it? After all, it only needs a first-class personality with a gift for that sort of thing (and it is a gift!) to devote about three months of his time to it, and travel enough assistants and props for a fit-up theatre around the country. Surely no organization would object to being deprived of one of their top men at irregular intervals for about a quarter of his working year?

Coming Clean

Even more valuable than a lecture for the public, however, would be a lecture every six months for the nuclear industry itself, for which the lecturer's qualifications would be almost impossibly stringent. He would have to be completely aware of everything that was going on, must be sufficiently eminent to resist gagging from high places, and sufficiently independent to assure freedom from bias. An appropriate title, in our opinion, would be the Epsom lecture, and its function would be to Tell All. A fairly mild example of the sort of thing in mind is Professor Blackett's recent Thomas Hawksley Lecture wherein he gently reminds us that we have tried to run too soon, and must go back and learn to walk. Now, even the most starry-eyed of us have realized for a long time that nuclear fusion has been gradually fading out of sight—but has anyone with authority ever publicly proclaimed it? And how many other projects have commenced with a blaze of publicity and then, when the ball of fire turned out to be a damp squib, have been kicked around in the hope that they can be quietly lost without anyone noticing?

There are, of course, stock answers to a plea for frank admission, in which the expressions "national prestige" . . . "dirty linen in public" . . . and similar bromides are dispensed. Let us be sure, however, that it is national prestige that is really at stake and not that of a handful of individuals. Furthermore, dirty linen, even if washed in public—and with Brand X, for that matter—is at least cleansed, even if the launderers emerge with their faces Washday Red.

Usual Disclaimer

Lest it should be imagined that we are hinting darkly at any particular project, let us hasten to add that we are not, so that if anyone is thinking of sending the boys round with their razors, they can forget it. But we seem to be still on the old merry-go-round; the AEA feels that industry doesn't always give it what it wants, and industry feels that the AEA doesn't tell them enough to be able to judge what it does want. So industry can't see why the AEA might really need a toolroom job on what would normally be common or garden ironmongery, and the AEA can't see why industry dislikes drilling 75-thou holes through 3-inch stainless steel—to choose a very minor example. If the cards weren't played so close to the waistcoat, and if a few more knew what everybody was doing, and why, life could be a lot simpler.

"Means Were Found . . ."

Watching hot metal being brutalized has always been one of our favourite pastimes, and we tottered along the other evening to see "Fashioned in Steel," the film that the English Steel film unit has just made for Darlington Forge. Between ourselves, we'd hoped to see the forging of the duct rings for AGR (we can't get away from that in this issue, can we?). Having done a little amateur blacksmith's work in our time, we have an immense respect for anyone who can forge a presentable gutter-bracket, let alone these particular rings, which are quite something, since the outer flange has to be cambered to fit into a cylindrical vessel—vastly more difficult than a sphere, in which our geometry books teach us that a hole is just a circle. It seemed to us that the production of this particular shape, plus the little refinements of grain flow, notch ductility and a few other trifles, needed a combination of a small miracle and know-how acquired since the days when young Mr. Stephenson wanted a tricky bit of blacksmithery for a successor to the "Rocket."

Well, it didn't work out. After watching, all agog, as the saying is (and few can be agogger than we can, when we give our mind to it) a most interesting film, we saw a ten-second shot of the finished ring, while the commentary told us that, owing to their peculiar shape, "special methods" of forging had had to be used. Our old acquaintance, the Ingenious Device, is with us once more. . . . Still, one can't expect everyone to lay bare their innermost secrets to satisfy mere vulgar curiosity, can one?

"This Blessed Plot . . ."

Never having been much for science fiction—some of the publicity material we get rather puts you off it—we do not propose to write a novel ourselves, but will dispose of a real hot plot at a reasonable price. Elsewhere in this issue is a brief notice of a new slave handling gear which, by a built-in tape memory, can be made to carry out operations on its own. This is to be the gimmick around which our plot revolves. The scene is a country house, taken over, for the purposes of our story, by the manufacturers of Poppets Plutonium Pellets—or some such name—and the cast, two male atomic scientists and one female ditto, attractive enough to have been the original cause of the Perturbation Theory, and having a weakness for Scientist A. Scientist B, unable to get anywhere with the girl (probably because his coat isn't Shining Shining White) attempts to remove A, by programming the machine to strangle him, but the machine puts up a black and strangles the managing director by mistake. A second attempt is unsuccessful because the girl (as they always do) wipes the tape in error and substitutes a programme which, intended for active waste disposal, writes off Scientist B in a vat of heavy water. So everyone is happy, because no one liked the managing director anyway.

Talking Point

Latest application of isotopes to be winnowed out of the sheaves of publicity material which flutter, thick as leaves in Vallombrosa, into our little nest, is a beta-emitting density gauge designed to detect portions of felt hats which have been unduly thinned by the stretching and shaping processes.

Speaking for ourselves, we very much prefer to have a thin spot in our hat. It makes it easier for talking through.

Sting-in-the-Tail Dept.

As a considerable amount of this issue is devoted to publicising the Advanced Gas Cooled Reactor, we can't resist having the odd irreverent slap, so here goes.

Let us give a great ovation,
A——G——R;
To the Second Generation,
A——G——R;
So compact and so much neater, all our problems you'll surmount
As you raise the thermal η an astonishing amount;
And, confounding your detractors, like a coruscating star
You outshine the old reactors,
A——G——R.

Yet, one thought that's not so funny,
A——G——R;
Are you going to save us money
A——G——R?
Will you really cut the ackers (if the figure is recalled)
To some five-and-eighty smackers for each kilowatt installed?
For, although we may agree it sounds a better job by far
We'll believe it when we see it
A——G——R.

It boils down, as all are seeing,
A——G——R;
Just to vulgar £ s d-ing
A——G——R;
Though efficiency enlarges an unlimited extent
Don't forget enrichment charges on the fuel you have to rent;
In the trend of present planning, there's a note that seems to jar
For—they've still got Magnox canning
A——G——R!

Tangent